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METALS PROCESSING LABORATORY
DEPARTMENT OF METALLURGY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

CAMBRIDGE, MASSACHUSETTS

Department of the Army, Ordnance Corps

Pitman-Dunn Laboratory

Frankford Arsenal

RESEARCH ON PARAMETERS INFLUENCING FLUIDITY IN ALUMINUM BASE ALLOYS

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ABSTRACT

Using the vacuum fluidity test, with small diameter tubes and low pressure heads, it was found that regardless of melt temperature, a "critical metal head" is necessary to force aluminum into small diameter channels. This "critical metal head" is that required to overcome surface tension. From experiments conducted it was calculated that surface tension of aluminum - 4.5 per cent copper alloy (oxide-free) was 590 dynes/cm. and surface tension of oxide-coated aluminum was 920 dynes/cm. When metal head in a fluidity test is very low (in the neighborhood of "critical metal head") surface effects are important in determining fluidity. Vibration has no effect in improving fluidity in the vacuum fluidity test.

Tests were conducted on the "critical metal head" necessary for metal to enter small diameter holes in sand molds. In this case, effective surface tension of aluminum - 4.5 per cent copper alloy was calculated to be the order of 800 dynes/cm. Vibration, applied to sand molds in such a way that it increases effective metal head, markedly increases the ability of the aluminum alloy to fill small diameter holes. For example, two inches below the melt surface in a sand mold the smallest hole metal will enter without vibration is 0.11 inches diameter; with vibration, holes smaller than .02 inches diameter can be filled.

Previous studies on effects of heat transfer on fluidity were continued. Fluidity in plaster molds is 300 per cent greater than that in silica sand. Increasing mold temperature of silica sand mold to 610°F. increases fluidity by 400 per cent.

Techniques of applying heat to mold-metal interfaces for the brief instant during mold filling were examined (since it should be possible to markedly improve fluidity by such a technique without significantly affecting solidification rate of a sand casting). Most promising results were obtained using electric resistance heating of a conducting layer at the mold-metal interface. Heat losses in runner systems were examined both analytically and experimentally and, for the types of gating system in commercial use, were found to be generally small or negligible.

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1. GENERAL INTRODUCTION

A. Previous Work

In July, 1957, a research program was sponsored at Massachusetts Institute of Technology by the U.S. Army Ordnance Department through Pitman-Dunn Laboratory, Frankford Arsenal, to obtain a basic understanding of the factors affecting fluidity in aluminum alloys and, if possible, to develop practical methods for increasing fluidity. During the first three years' research on this program, tests were developed and employed to isolate the important variables affecting fluidity, and theoretical and experimental analyses were used to relate metal fluidity to (1) solidification mode, (2) surface tension and surface oxide films, (3) superheat, and (4) other metal and mold variables. In addition, completely practical methods were developed to increase fluidity of aluminum alloys (in production) by as much as a factor of three, and it was shown that by improving fluidity, significantly higher mechanical properties can be obtained in aluminum alloy sand castings. Results during the first three years of this program have been reported in detail (1-10); in summary, they include:

(1) A new type of sand mold fluidity spiral was developed which permits study of the effect of metal, metal-mold, and mold variables (on fluidity of aluminum alloys). The test permits close control of metal pressure head and introduces the metal smoothly and free of dross. Originally, the test mold consisted of a single test spiral plus attached gating system; later a second spiral was attached to serve as a "control" in the study of mold and metal-mold variables. Reproducibility of this test was shown to be $\pm$ 1 inch of metal flow.

(2) Metal-mold variables were examined from a theoretical standpoint and were studied experimentally in the test pattern described above to assess their importance in determining metal fluidity. Specifically, variables considered included surface tension, surface oxide films, mold atmosphere, and heat transfer and fluid flow variables as they are affected by condition of the metal-mold interface.

(3) A wide variety of mold coatings were tested to determine their effect on fluidity in the sand mold fluidity test; coatings were chosen that were considered to have an important effect on one or another of the variables mentioned in (2) above. Certain of these coatings were shown to improve fluidity by up to 300 per cent. Hexachloroethane (C_2Cl_6) was found to be most effective but other coatings were also found to improve fluidity; these included amorphous carbon, hexachlorobenzene, zinc carbonate, calcium carbonate, iodine and others.

(4) A flat plate casting was designed to test the effect of mold coatings on fluidity in a simulated production casting. Large increases in fluidity were obtained with hexachloroethane coatings and with carbon black coatings. In the case of aluminum - 4.5 per cent copper alloy a .003" thick coating of hexachloroethane permitted filling the plate at approximately 1300°F. pouring temperature. In the absence of the coating the cavity did not fill completely at 1450°F.

(5) Mold coatings studied in detail (hexachloroethane and carbon black) have no deleterious effect on X-ray quality or surface appearance of aluminum castings. In addition to improving fluidity, these coatings can significantly improve mechanical properties by permitting reduced pouring temperatures. For example, in an aluminum - 4.5 per cent copper

alloy test casting, coatings permitted lowering the pouring temperature 100°F; as a result, elongation was increased from 4 to 8 per cent with a simultaneous increase in tensile strength.

(6) Effects of a variety of mold variables on fluidity were examined. Fluidity in green sand molds was substantially unaffected by change in grain size, moisture content, or by small addition of sand additives such as cereal and sawdust. Substituting zircon sand for silica sand decreased fluidity.

(7) Fluidity in core sands was found to be 20 to 50 per cent less than fluidity in bentonite bonded green sand molds. Core sands studied included those bonded with sodium silicate, linseed oil, and phenolformaldehyde. The decreased fluidity in the core sand molds was apparently due to more rapid heat extraction.

(8) A "vacuum fluidity test", developed in a previous study, was modified for use with aluminum alloys. This test permits study under carefully controlled conditions of the effect of metal (and other) variables on fluidity.

(9) Fluidities of aluminum-tin alloys, aluminum - 4.5 per cent copper alloy and aluminum - 4.5 per cent copper alloy containing added third elements were studied in the "vacuum fluidity test". High-speed photography was used to determine progress of metal flow in the (glass) fluidity channel; metallography and chemical analyses were employed to aid in interpreting the effects of metal variables on fluidity.

(10) Mode of solidification of alloys in the fluidity test channel was shown to be markedly different from pure aluminum. Alloys such as aluminum - 10 per cent tin and aluminum - 4.5 per cent copper

stop flowing primarily because of solidification at or near the tip of the flowing stream; in pure aluminum the solidification which stops flow is at or near the entrance of the test channel. Differences in fluidity and fluid behavior between pure aluminum and its alloys were shown to be largely accounted for by differences in modes of solidification.

(11) Effect of atmosphere on fluidity was studied using the "vacuum fluidity test." Atmospheres studied included nitrogen, argon, chlorine, and atmospheres containing various percentages of oxygen. It was found that changing the atmosphere had no effect on fluidity or fluid flow unless the atmosphere resulted in deposition of a surface film on the mold (as, for example, chlorine resulted in formation of an aluminum-chloride coating on the mold surface under certain conditions of testing).

(12) Effects of third elements on fluidity of aluminum - 4.5 per cent copper alloy were studied. Elements added (in amounts up to 3 per cent) included iron, manganese, cobalt, chromium, beryllium, silicon, magnesium, calcium, and copper. Effects of these elements on fluidity were not large. Maximum improvements were 25 per cent at 1 per cent beryllium, and 28 per cent at 1 per cent cobalt.

(13) Effects on fluidity of third elements added were attributed to (a) increased superheat resulting from the lower liquidus temperature, (b) narrower temperature range of solidification, and/or (c) change in the nature of primary crystals which formed.

(14) Vibration had no effect on fluidity in the vacuum fluidity test; grain refinement by vibration decreased fluidity slightly (10 to 13 per cent).

(15) Theoretical analysis led to the conclusion that fluidity results obtained and summarized above were not influenced by changes in factors such as surface tension, surface films, or viscosity. As would be expected, test variables including metal head, metal superheat, and thickness of test casting affect fluidity test results; in addition to these, the factors found to be significant were (a) mode of solidification, and (b) heat transfer.

(16) Analyses on effects of mold coatings on fluidity led to the conclusions that (a) the major factor leading to improved fluidity is the insulating effect of mold coatings; i.e., the coatings improve fluidity primarily by slowing heat transfer at the metal-mold interface, and (b) a second factor, at least in the vacuum fluidity test, may be a slight reduction in metal-mold friction ("lubricating" effect) due to the coatings.

(17) An equation was developed to express fluidity of "mushy" freezing alloys in terms of metal and mold variables. The equation is in qualitative and/or quantitative agreement with test results and accounts for a variety of observed feature of fluidity of alloys including (a) linearity between fluidity and superheat, (b) finite fluidity at zero superheat, (c) effect of heat of fusion on fluidity, (d) effect of pressure head on fluidity, (e) proportional dependence of fluidity on the ratio of cross-sectional area to circumference, (f) decrease in fluid life with increase in pressure head, (g) effect of mold coatings on fluidity, and (h) effect of grain refinement on fluidity.

B. Current Work

Research conducted in the preceding six months of this program is described herein. It is a continuation of earlier work directed primarily at studies of (1) effects of surface tension and vibration on the ability of metal to enter small diameter test channels and on fluidity of metal in these test channels, and (2) continuing study of effects of heat transfer variables on fluidity in standard size test channels (the order of 1/8-inch thick).

Section II of this report describes work conducted on effects of surface tension and vibration on metal flow, using the vacuum fluidity test. This work was undertaken as an extension of previous studies into an area of fluidity which had not been heretofore examined - fluidity in very small tubes using very small metallostatic heads. It was anticipated that under these conditions surface tension would begin to become an important influence on the ability of metal to enter small holes and on the distance metal would flow once it succeeded in entering these holes; it was further anticipated that vibration might have some influence in these instances where it does not in other types of fluidity tests.

Section III describes similar work conducted using a sand mold test but with very small diameter channels. In this, as in work using the vacuum fluidity test, the aim was to determine effects of surface tension and vibration on metal flow in small diameter test channels. In this work on sand molds, vibration was applied in such a way that it increased metallostatic head at the test channel opening.

A final section of this report, Section IV, describes research conducted during the last three to six months on methods of minimizing heat losses during the filling of a casting cavity. Specifically, techniques examined were (1) increasing mold temperature, (2) decreasing mold diffusivity, (3) applying heat to the mold-metal interface during the filling of casting cavity, and (4) applying heat to a runner system during filling of a casting cavity. An appendix is included which presents a theoretical analysis of heat losses in runners, and compares theory with experiment.

II. SURFACE TENSION, VIBRATION AND FLUIDITY - VACUUM FLUIDITY TEST

A. Preliminary Tests

Intuitively, it is convincing to argue that vibrating molds may break the surface film on liquid metal and enhance flow into intricate parts of the mold cavity. Previous work, for example, indicates that mold vibration increases penetration in sand molds [11], increases sharpness of detail in investment molds, and permits metal to flow into very thin sections where it would not normally penetrate (sections from .060 inches to about .005 inches in diameter in the case of 195 alloy)[12]. It was therefore anticipated that vibration might have some effect on fluidity by breaking the surface oxide film as discussed above; it might also affect fluidity in some other way, as by (1) affecting mode of solidification, (2) altering the condition of contact between metal and mold and thereby changing resistance to fluid flow and/or heat flow at the mold-metal interface, or (3) instantaneously changing effective metallostatic head.

In a preliminary series of experiments conducted during fiscal year 1959 - 1960, effect of vibration on fluidity was studied using the vacuum fluidity tester, Figure 1. In this test, metal of known composition and temperature is drawn into the fluidity test channel under predetermined pressure head. The distance the metal runs into the tube is taken as the measure of fluidity. When glass tubes are used for the fluidity test channel, progress of metal flow can be measured by motion picture photography, permitting determination of flow velocity and "fluid life" (time of flow).

The difference between atmospheric pressure and the controlled partial vacuum in the reservoir bottle is the pressure difference which forces metal up the fluidity test channel. This difference is measured with a manometer, either mercury or water. In all work reported herein, the pressure difference was converted to an equivalent "metal head." For example, when a mercury manometer and horizontal test channel were used (Figure 2a), the following formula was employed to convert pressure differences to "metal heads."

$$H = \frac{\rho_{Hg}}{\rho_a} \cdot P_{H_g} \cdot 0.0394 - \Delta H \qquad (1)$$

where:

H = pressure "head" on flowing stream expressed in inches of the metal (aluminum - 4.5 per cent copper alloy)

ρ_{Hg} = density of mercury (gms/cc)

ρa = density of the aluminum alloy employed at the melt temperature (gms/cc)

P_{H_g} = reading on mercury manometer (mm)

ΔH = difference in height between horizontal portion of the test channel and top of metal bath (inches)

0.0394 = conversion factor from mm to inches

The density of liquid aluminum - 4.5 per cent copper alloy was taken as 2.42 grams/cc for all work, including the alloys with small additions of the third elements, and ΔH was held constant at two inches; hence the equation becomes:

$$H = 0.22\ P_{H_g} - 2 \qquad (2)$$

Not all fluidity tests were conducted with bent tubes as shown in Figure 2a. For experimental convenience, particularly in the case of small diameter tubes, straight tubes were used where noted. In these cases, the angle of elevation was kept to a minimum and the last term in equations (1) and (2) was neglected.

Complete detailed descriptions of the operating procedure of the vacuum fluidity tester may be found in a recent report [3]. In subsequent parts of this report, only procedures which differ from those previously employed are described in detail.

In these preliminary studies, a series of tests were conducted using an electro-magnetic vibrator with a fixed frequency of 60 cycles per second and an amplitude of .007 inches. In one set of tests, tubes were employed whose inside diameters were 0.20 inches, .16 inches and 0.12 inches. Vibration was applied both parallel and lateral to the metal flow direction as sketched in Figures 2a and b.

Several different metal heads and pouring temperatures were employed, as listed in Table I. High metal heads were used to obtain high velocity and emphasize effects of wall friction and of thermal contact resistance. Lower heads were used to emphasize effects of surface films; smaller tubes were expected to emphasize effects of all three factors (surface films, friction, and thermal contact resistance). Results of these tests, presented in Table I, indicate no significant effect of vibration on fluidity.

In an additional attempt to emphasize effect of surface films a series of tests were run using tubes only .07 inches inside diameter. In this case, vibration was as shown in Figure 2c. All tests were conducted at a pressure head equivalent to 30 inches of metal, with temperature varied from 1200° - 1475°F. Figure 3 shows that vibration had no significant effect on fluidity.

B. Fluidity in Small Tubes at Low Pressure Heads

In order to confirm the findings that fluidity is not affected by vibration in the vacuum fluidity test, a series of tests were made using small diameter tubes (.07 inches) and low pressure heads. (Any effects of vibration should be most marked with these experimental conditions.) A series of tests were first run using no vibration and using pressures equivalent to metal heads of 30, 10, 5, 4 and 3-1/2 inches. These data are plotted in Figure 4, and when additional tests were made using vibration (as sketched in Figure 2c) identical results were obtained. Again, vibration had no effect on fluidity.

When the fluidity data obtained at the low pressures were re-plotted versus "metal head", the curves shown in Figure 5 were obtained. For metal heads above about 4 - 6 inches the expected relationship between fluidity and metal head was found; however, below this metal head, fluidity dropped rapidly and below 2 - 3 inches no metal entered the tube regardless of melt temperature. It was concluded that a "critical metal head" in the neighborhood of 2 - 3 inches was required (from surface tension considerations) to force metal into the small diameter tube.

Special fluidity tests were then made to determine more precisely this critical metal head. To measure the pressure accurately, a water manometer was substituted for the mercury manometer and to eliminate effects of solidification variables, the fluidity test tube was dipped in the metal for at least ten seconds before applying the vacuum, thus heating the tube to the temperature of the metal.

Thereafter, vacuum was applied for ten seconds, the tube taken out of the metal, vacuum valve closed, and then the tube was examined. Tests were run in the range of 1300° - 1400° F.; tubes .07 inches in diameter were employed.

Regardless of metal temperature, it was found that when the pressure was higher than 6.7 inches of water, metal always entered the tube, and when the pressure was less than 5.9 inches, no metal ever entered the tube. Averaging of these limits and converting to inches of metal head yields 2.6 inches as the "critical head" required to force aluminum into the tube (Figure 5).

Assuming the "critical metal head" measured is that required to overcome surface tension, and assuming the contact angle between metal and mold is 180° (i.e., no "wetting"), the effective surface tension can be calculated from:

$$\gamma = \frac{d \rho g \quad h}{4} \tag{3}$$

where:

γ = surface tension (dynes/cm)

d = tube diameter (cm)

ρ = metal density (gms/cm^3)

h = "metal head" (cm)

Substituting:

$$\gamma = 1/4 \quad (.07 \times 2.54)\ (2.4)\ (980)\ (2.6 \times 2.54)$$

$$\gamma = 690 \text{ dynes/cm.}$$

This value is quite reasonable, lying between results previously recorded for oxide-coated aluminum (840 dynes per centimeter), and for oxide-free aluminum (520 dynes per centimeter)[13].

In order to determine if vibration had any effect on "critical metal head" required to force metal into the small diameter tube, a series of twenty tests were made with and without vibration. These tests were again made with .07 inches diameter tubes, pouring temperature in the range of 1300 - 1400°F., and with metal heads from 0 to 3.5".

Both lateral and longitudinal vibration were employed. Vibration had no effect on critical metal head.

C. Effect of Atmosphere on Surface Tension and Fluidity

Because surface tension was shown to have some influence on fluidity in very small diameter tubes at low pressure heads, it was decided to re-examine the effect of atmosphere on surface tension and fluidity under these conditions; effects of nitrogen and oxygen were studied. For tests in nitrogen atmosphere the following procedure was employed:

Metal (aluminum - 4.5 per cent copper alloy) was melted and held at 50° - 100°F. above its liquidus temperature. Pyrex tubes (.07 and .20 inches in diameter) were heated to their softening point and then cooled while passing dry nitrogen through them. Pressure in the vacuum reserve tank was adjusted to a predetermined value using a water manometer. Next, the pyrex tube was dipped into the melt (in vertical position) while still passing nitrogen through it. After some bubbling, the nitrogen was shut off and the tube kept in the melt until it became as hot as the melt. The test was then conducted by opening the vacuum valve and determining whether the metal in the tube reached the level of the melt, or was above or below it.

For tests conducted in oxygen atmosphere, the steps were essentially similar to those above, except that after drying the tube with nitrogen, oxygen was substituted for nitrogen in the remaining steps.

A series of eighteen tests were conducted and results are summarized in Table II. Metal heads are listed that were required under a given set of experimental conditions to draw metal into the fluidity tube and bring it level with the surrounding bath. For example, 1.9 inches of metal head were required in the case of tests conducted in the large diameter tube in nitrogen atmosphere. Larger heads were required in smaller tubes and in oxygen atmosphere.

Using equation (3), surface tension in nitrogen atmosphere in the large tube is calculated to be 550 dynes/cm; in the small tube it is calculated to be 625 dynes/cm. These results average to 590 dynes per centimeter $\pm$ 7 per cent and are closely comparable to the 520 dynes per centimeter reported for oxide-free aluminum (13). In oxygen atmosphere surface tension is considerably higher and is calculated to be 920 dynes per centimeter; this roughly is the value to be expected for oxide-coated aluminum.

Based on the above results, Figure 6 shows how surface tension in oxide-coated and oxide-free aluminum affects the minimum metal head required to force metal in a small diameter tube. As tube diameter decreases below about 0.10 inches, the head required to force metal to enter increases rapidly.

In conclusion of this phase of the study, experiments were conducted to determine if any effect of atmosphere on fluidity could be discerned (i.e., effect of atmosphere on distance the metal would run in the test channel). Fluidity tests were made in both nitrogen and oxygen atmospheres with tubes 0.20 inch and 0.06 inch diameter. Within the limits of experimental accuracy, no effects of atmosphere on fluidity were found, and this was not unexpected as may be shown by a simple example:

Consider, as example, that the data in Figure 5 apply to flow of oxide-free aluminum. At 1200°F. pouring temperature and with 10 inches of metal head, fluidity is 0.9 inches. From Figure 6, the equivalent metal head to be lost if an oxide film is present is 1.5 inches since tube diameter is .07 inches. From the data in Figure 5, this decrease in metal head will result in a decrease in fluidity of less than .08 inches. Atmosphere would affect fluidity appreciably only at very low pressure heads, in the neighborhood of the "critical head" required to overcome surface tension.

It is of interest that marked differences in surface appearance were found between the specimen cast in nitrogen and those cast in oxygen. The surfaces of specimens cast in the nitrogen atmosphere were generally smooth and white, indicating absence of oxide and non-wetting. The surfaces of specimens cast in oxygen were generally full of cracks, indicating oxide films. In some of the experiments, liquid metal was sucked into the tubes where it remained liquid because the tubes were preheated. This liquid was then blown out after the level was checked. In the nitrogen cast specimens, the metal was completely blown out; however, in the specimens cast in oxygen atmosphere thin metallic films were found all along the inside of the tube, indicating wetting between the oxide-coated metal and glass, and possibly chemical combination between them.

D. Conclusions

1. Vibration (60 cycles per second) applied parallel and perpendicular to direction of flow in the vacuum fluidity test was found to have no effect on fluidity. This was the case even in tubes as small as .07 inches in diameter and at metal heads as low as 3.5 inches.

2. Regardless of melt temperature, a "critical metal head" is necessary to force aluminum into small diameter channels. This critical metal head is that required to overcome surface tension.

3. Calculations based on a series of experiments conducted in normal atmosphere indicated effective surface tension of aluminum - 4.5 per cent copper alloy was 690 dynes/cm. Surface tension in nitrogen atmosphere was calculated to be 590 dynes per centimeter and in oxygen atmosphere to be approximately 920 dynes per centimeter. These values are in general agreement with published data for surface tension of aluminum.

4. Vibration has no effect on the "critical metal head" required to force metal to enter small diameter channels; hence, it apparently has no effect on surface tension.

5. When the metal head in a fluidity test is somewhat greater than the "critical metal head", no significant effect on fluidity is obtained by altering surface effects; e.g., by adding or removing an oxide film.

(6) When the metal head in a fluidity test is very low (in the neighborhood of the "critical metal head") surface effects are important in determining fluidity.

III. SURFACE TENSION, VIBRATION AND FLUIDITY - SAND MOLDS

A. Introduction and Experimental Procedure

After having established that vibration had no appreciable influence on fluidity in the vacuum fluidity test, a study was initiated on the effect of vibration on fluidity in sand molds. After preliminary tests, a total of twelve cylindrical castings were made and reported on herein. The type casting studied was a cylinder two inches in diameter by five inches high, bottom gated (Figure 7). After molding the cylinder and gating system, small holes of different sizes were made on the side walls and on the bottom of the cylinder at various heights in the mold cavity. Diameters of these holes were measured on the castings after solidification and were .02 to .20 inches in diameter. In most castings, seven different sized holes were punched; these were .02, .03, .045, .06, .095, .13, and .20 inches in diameter. Figure 8 is a photograph of one typical test casting produced.

The alloy used in all studies was aluminum - 4.5 per cent copper alloy (high purity), except that in one casting 0.5 per cent beryllium was added to the melt. Molds were bentonite bonded, synthetic green sand, of AFS No. 110, with 3.5 - 3.8 per cent moisture; they were rammed in a rigid metal flask.

An electro-magnetic vibrator was used for those castings which were vibrated; this was the same equipment used for vibration studies in vacuum fluidity tester. The vibrator has a fixed frequency of 60 cycles per second and a maximum amplitude (half cycle) of .0035 inches. Tests were run at amplitudes varying from .001 inches to .0035 inches, with the amplitude of each test measured by touching a dial gauge to the vibrating mold. Vibration was applied in the vertical direction. The flask was clamped firmly on top of the vibrator and the entire assembly suspended by wires from a horizontal crosspiece.

In an additional series of experiments, vibration (60 cycles, .0035 inch amplitude) was applied vertically to (1) a standard double spiral sand mold fluidity test, and (2) a standard test plate pattern 5" x 5" x 1/8" thick. Both these tests have been used extensively in earlier research on this program and have been described in detail.[3]

B. Effect of Surface Tension on Ability of Metal to Enter Small Holes

It was first found in this study that for unvibrated castings, surface tension effects are similar in the sand mold to those in the vacuum fluidity test. That is, for any given metal head, there is a minimum size hole which metal will enter. For example, at a point one inch below the top surface of the metal in the casting, the smallest hole into which metal will run is approximately 0.2 inches; four inches below the surface, metal will flow into a hole approximately 0.05 inches in diameter, Figure 9.

Results obtained in this phase of the study were quite reproducible and clearly attributable to surface tension effects; Figure 10 compiles data from four unvibrated castings. Calculating surface tension from these data, using Equation 3, a value of 800 dynes per centimeter fits well all experimental results. This compares with values of 840 dynes per centimeter for oxide-coated aluminum and 520 dynes per centimeter for oxide-free aluminum reported[13]. It compares also with results from the vacuum fluidity test reported in Part II of this report (590 dynes per centimeter for oxide-free aluminum and 920 dynes per centimeter for oxide-coated aluminum). It should be noted that the data referenced applies to pure aluminum but results would be expected to be comparable to aluminum - 4.5 per cent copper alloy.

Beryllium is sometimes added to aluminum alloys in the belief that it alters the oxide film on the flowing stream - and in many aluminum alloys, including aluminum - 4.5 per cent copper alloy, small additions of beryllium do change the appearance of the molten metal to some degree. To examine the effect of beryllium on surface tension, a single casting was poured of aluminum - 4.5 per cent copper - 0.5 per cent beryllium alloy. However, no effect of beryllium on surface tension was found.

C. <u>Effect of Vibration on Ability of Metal to Enter Small Holes</u>

Effect of vibration on fluidity was next studied by vibrating the sand test casting in a vertical direction during filling of the mold and for a short time after filling. Vibration resulted in significantly greater ability of the metal to run into the small diameter holes. For example, in one vibrated casting, holes were run that were less than half the diameter of the smallest holes the metal entered in comparable location in the unvibrated casting (Figure 11). Figure 12 is photographic evidence of the marked effect of vibration on ability to fill small holes in sand castings.

The effect of vibration in improving fluidity is markedly dependent on vibration amplitude. For example, the data in Figure 11 refer (for the vibrated casting) to a vibration amplitude of .001 inches. Much greater improvement is possible with larger amplitudes. Figure 13 summarizes the data obtained for amplitudes varying from .001 inches to .0035 inches. In general, increasing amplitudes permit smaller holes to be filled at a given metal head. Surprisingly, when amplitudes as great as .003 inches to .0035 inches are employed, all holes fill regardless of their location in the casting.

Vibration, then, clearly has marked effect in increasing the ability of metal to run into small holes in the sand mold test casting. This is in spite of the fact that no effect of vibration whatever was discerned in the vacuum fluidity test. The major difference appears to be that in the sand mold test, vibration is applied in such a way that it acts to increase <u>effective metal head</u>. That is, the rapid vertical vibration must momentarily increase the pressure of the metal against the mold wall (from acceleration effects). A simple calculation to determine the magnitude of this effect can be made assuming sinusoidal type variation. Vibrational displacement is then:

$$X = A \sin 2\pi nt \qquad (4)$$

where: X = displacement (cm)

A = amplitude (cm)

n = frequency (cycles per second)

t = time (seconds)

and maximum acceleration, obtained by maximizing the second derivative of equation (4) is:

$$a_{max} = 4A(\pi n)^2 \qquad (5)$$

where:

a_{max} = maximum acceleration (cm/sec^2)

From equation (5), the maximum acceleration obtained at the lowest amplitude employed in this work (.001 inches) was 360 cm/sec, or 0.37 times gravitational acceleration. At the highest amplitude (.0035 inches) maximum acceleration was 1260 centimeter per second, or 1.3 times gravitational acceleration.

The above figures were approximately checked by simple experiments. A small weight was first placed on the vibrator and amplitude increased gradually until it started jumping slightly. This amplitude corresponded closely to that calculated from equation (5) to be the amplitude where vibrational acceleration equaled gravitational acceleration (.0027 inches). Then by use of a lever system the equation was checked in similar fashion at lower amplitudes, and it was concluded that equation (5) accurately described the maximum acceleration of the vibrator.

With the maximum acceleration calculated from equation (5) the increase in effective metal head as a result of vibration can be readily calculated:

$$h = \left[\frac{g + a_{max}}{g} h' \right] \qquad (6)$$

where:

h = effective metal head (cm or inches)

h' = height of metal above test channel (cm or inches)

and by combining (3) and (6) the effect of vibration on the minimum size hole that metal can enter is:

$$d = \frac{4\gamma}{\rho h' \; (g + a_{max})} \qquad (7)$$

where:

d = diameter of minimum size hole metal can enter (cm)

h' = height of metal above hole (cm)

At the lower amplitudes employed in this work, the effect of vibration in increasing the ability of metal to flow into small holes is quite near that predicted by equation (7). Calculated and observed data for "minimum hole diameter" versus vibration amplitude are listed in Table IV, and for amplitudes up to .0025 inches agreement is well within experimental error.

At amplitudes above .0025 inches, results do not correspond at all to the simple theory outlined above. At these amplitudes, metal entered the smallest hole made regardless of the metal height over the holes. A reasonable explanation for this may be found in the fact that at the higher amplitudes (.003 and .0035 inches) gravitational acceleration was exceeded (calculation and experiment cited earlier indicated that at .0027 inches amplitude maximum vibrational acceleration was equal to gravitational acceleration).

With maximum vibrational acceleration greater than gravitational it seems likely that the molten metal would not remain in intimate contact with the mold walls on the downward cycles. On upward cycles considerably higher instantaneous pressures might then be obtained and result in the filling of smaller holes than would otherwise be possible.

D. Effect of Vibration on Fluidity in Small Holes

The preceding sections have considered the influence of surface tension and vibration on the ability of metal to enter small diameter holes in sand molds. In addition, several controlled experiments were conducted to determine the effect of vibration on fluidity in the holes - on the distance the metal runs once it enters small diameter holes.

Two castings (Castings No. 11 and 12) were poured and completely filled before vibration was started. This was done so that the metal head over each hole was precisely known at the beginning of vibration. The distances metal ran into the holes in these castings were then compared with those in two unvibrated castings poured under similar conditions (Castings No. 3 and 4).

In the unvibrated castings, in spite of considerable scattering, fluidity was roughly a linear function of metal head. As would be expected from studies described earlier in this report there was, for each size hole, a minimum metal head below which fluidity was zero. At higher heads, fluidity increased rapidly, Figure 14.

Vibration increased fluidity appreciably, particularly at the lower metal heads. In both the vibrated castings, finite fluidity was attained at even the lowest metal head studied. Figure 15 shows the data obtained for one of the two castings. This casting was vibrated at an amplitude of .0035 inches; the other casting yielded similar data, with slightly lower fluidity (vibration amplitude was .003 inches).

As in the instance of vibration improving the ability of metal to enter small holes, it appears that the explanation for the above lies in the increased effective metal head resulting from vibration. In agreement with experimental results, such a mechanism would tend to improve fluidity most markedly at lower metal heads - in the region near the "critical metal head".

E. Effect of Vibration on Fluidity in Standard (1/8 inch thick) Sand Mold Fluidity Tests.

A brief series of experiments were conducted to determine if vibration might have some beneficial effect in types of castings of immediate interest to sand foundrymen (castings with sections 1/10" and above). Tests were conducted using the green sand mold double spiral and flat plate test pattern (5" x 5" x 1/8") used extensively in earlier parts of the research and described in detail earlier.[3]

Testing procedure in this work was identical to that used and described earlier, except that here some castings were vibrated vertically (.0035 inches amplitude) and others poured with no vibration to serve as controls. No improvement in fluidity in either type test was found and, to the contrary, there was some consistent indication that vibration decreased fluidity (an example is shown in Figure 16). Vibrated castings generally had a rougher surface than unvibrated castings, particularly at higher pouring temperatures, and it is surmised one effect of vibration was to cause the metal to penetrate between the sand grains more completely - thereby decreasing thermal contact resistance and hence decreasing fluidity.

F. Conclusions

1. "Critical metal head" necessary for metal to enter small holes in sand molds was measured and related to surface tension. Data obtained for unvibrated castings indicate the effective surface tension of aluminum - 4.5 per cent copper alloy in sand molds in the order of 800 dynes per centimeter.

2. Beryllium addition has no effect on the ability of aluminum - 4.5 per cent copper alloy to enter small diameter holes.

3. Vibration (60 cycles per second with amplitudes from .001 to .0035 inches) markedly increases the ability of the aluminum alloy to fill small diameter holes. For example, 2 inches below a melt surface the smallest hole metal will enter without vibration is 0.11 inches diameter; with vibration amplitude of .002 inches it can enter a hole

.07 inches in diameter and with vibration amplitude of .003 inches it can enter a hole smaller than .02 inches.

4. The effect of vibration in improving the ability of metal to enter small diameter holes is explainable qualitatively and quantitatively on the basis that vibration increases effective metal head.

5. Vibration increases the distance metal runs (fluidity) in small holes in sand molds; this effect is greatest at small metal heads and is again attributable to increased effective metal head.

6. No increase in fluidity was found from vibration in the case of (a) a standard sand mold fluidity spiral (1/8 inch thick) and (b) a plate-like sand casting (1/8 inch thick).

IV. IMPROVING FLUIDITY BY CONTROL OF HEAT TRANSFER

A. Introduction

Results of all research conducted in this program to date have shown that for sections of immediate interest to sand foundrymen (1/10 inch thick and above) fluidity is not influenced by changes in factors such as surface tension, surface films, or metal viscosity. It is, of course, affected by test variables such as metal head, metal superheat, and thickness of test casting; in addition, factors found to have significant effects on fluidity were (a) mode of solidification, and (b) heat transfer.

In work reported earlier, extensive attempts were made to alter mode of solidification of aluminum - 4.5 per cent copper alloy in order to improve fluidity. In addition, studies were conducted on improving fluidity by altering heat transfer, and mold coatings were developed which decreased rate of heat transfer and so improved fluidity. It was concluded that the only way to significantly improve fluidity of a given alloy in a mold of a given configuration (of 1/10 inch section or thicker) was to alter heat flow characteristics.

As a result of the above, it was decided to continue research during this fiscal year in the direction of heat flow studies. Initial work was conducted using the green sand mold double spiral test pattern, Figure 17, which has been described in detail in earlier reports. Other tests were also used for brief studies and these are reported and described later.

B. Effect of Mold Material and Mold Temperature on Fluidity

Earlier work has shown that the two heat flow variables of greatest importance in determining fluidity are (1) mold-metal contact resistance and (2) heat diffusivity of the mold material. Mold coatings increase fluidity by decreasing mold-metal contact resistance and "chilling" sands (e.g. zircon sand) decrease fluidity because of their increased heat diffusivity.

To obtain comparable data for fluidity in a mold material with very low heat diffusivity, tests were made on fluidity in plaster molds. The spiral patterns themselves were molded in plaster, approximately ½ inch thick. The plaster was then backed with bentonite-bonded silica sand, 110 A.F.S. fineness number. Thus, composite molds were made which had the sprue and runner system in sand as was the case in all previous work, but the spirals themselves were in plaster. The molds were baked for eight hours at 400°F. and allowed to cool to room temperature before pouring. Melting and pouring practices were as described in similar previous work. Results obtained are given in Figure 18 and show an increase in fluidity of about 300 per cent, in the range of 1250 - 1350°F. This is considered to be in large part due to the lower heat diffusivity of plaster (1.02×10^{-2} as compared to 6.45×10^{-2} for silica sand and 10.4×10^{-2} for zircon sand*).

An effect similar to lowering of mold diffusivity is obtainable by heating a mold of a given heat diffusivity to a temperature substantially above room temperature. To investigate the magnitude of this effect, molds were made of the "standard" green sand mix used in earlier studies (bentonite-bonded 110AFS sand). Some of these molds were poured at room temperature, and others were baked at elevated temperatures for about eight hours. The temperature of the molds at the time of pouring was measured using thermocouples placed at the parting line and connected to a sixteen-point recorder.

Results of these tests are presented in Figure 19 for three different mold temperatures, 80°F., 450°F., and 610°F. The fluidity curve for molds at 80°F. represents fluidity in molds that were not

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* Values calculated in the vicinity of the pouring temperatures employed, using data from Ruddle [15].

baked (contained approximately 3.5 per cent water); however, it will be recalled that there is no difference in fluidity between green and baked sand molds providing these molds are at the same temperature at the time of pouring [3].

The 450°F. mold temperature resulted in an improvement of 250 per cent in fluidity and the 610°F. mold temperature improved fluidity about 400 per cent in the 1200 - 1400°F. temperature range. These increases are quite large and are somewhat larger than would be calculated from the mathematical analysis developed earlier[3] (if mold-metal contact resistance is assumed to be unaltered). However, it is quite possible that increasing mold temperature could, in some way, alter this mold-metal resistance.

C. Improving Fluidity by Resistance Heating.

The filling of mold cavities takes place in an extremely short time (in the case of a fluidity test spiral it is less than a second) and if it were possible to instantaneously heat the mold-metal interface to very high temperatures during this brief filling period, then very large increases in fluidity could be obtained. Furthermore, since only the interface would be heated, the solidification rate of the casting should be substantially unaltered (once the mold was filled and the heat turned off).

In searching for a practical way to accomplish this heating, a variety of methods were considered, including induction, high frequency radio, resistance, etc. The most feasible of these, and the only one which has been tested in experiment, is resistance heating.

To test the feasibility of resistance heating, fine layers of amorphous carbon (approximately .005 inch thick) were placed on sand molds by spraying an alcohol suspension of the material. Using voltages up to 300 volts, coatings could be heated to red-heat within approximately 2 seconds.

Preliminary tests were made using the thin-plate fluidity test (5 inches x 5 inches x 1/8-inch) described earlier. Experimental technique was to place one electrode in the runner and one at the end of the plate away from the runner; the plate and runner were coated with amorphous carbon. As the liquid metal entered the runner, the electric circuit was completed and current was passed through the amorphous carbon coating. In these preliminary tests, no significant improvement in fluidity was obtained. However, there is no apparent reason why the technique should not be feasible and fully practicable, with more research on suitable techniques of application and electrical manipulation.

D. Heat Losses in Runners

One area where heat flow might significantly affect fluidity is in the runner system of a filling cavity. To date, there has been little published information on heat losses in runner systems and it is conceivable that in at least certain types of designs the heat losses might be great enough to substantially lower fluidity. If this is true, then systems to minimize these heat losses should be quite practical means of improving fluidity in commercial foundries. Furthermore, the possibility of adding superheat to a runner system itself should not be overlooked. For a variety of reasons, temperatures much above 1400°F. are undesirable in melting of aluminum alloy; however, if metal could be poured at, say, 1350°F., and instantaneously heated to 1500°F. or above as it flowed through a runner cavity, these same disadvantages might not be present.

In these studies, heat losses to be expected were first analysed mathematically (Appendix). With the assumptions employed, results showed that only a very small temperature drop could be expected in aluminum alloys in the types of gating systems employed in commercial practice.

In one test conducted to confirm this, metal was poured down a simulated runner system, which had a vertical sprue entering directly into a one-inch diameter channel, 16 inches long. A slight choke was placed at the end of the channel to keep it full during pouring. Thermocouples were placed at the entrance and exit of the horizontal channel. Flow rate was .35 pounds per second of aluminum, corresponding to a flow velocity of 80 inches per second. The temperature drop recorded in the runner system itself was at most 5°F. This maximum drop was observed a second or two after start of pour; thereafter temperature loss decreased. The small temperature drop observed was approximately that which would be calculated using equation 9 of Appendix.

Some exploratory experiments and calculations were also conducted to determine the feasibility of very rapidly superheating metal within runner systems. The three systems examined were resistance heating, induction heating, and induction heating with a graphite susceptor. In all instances, the power requirements were so great (because of the rapid flow of aluminum in typical commercial gating systems) that it was concluded that such an approach is not practical at the present time. For example, some calculations were made to assess the intensity of current which would be required to heat metal in the runner system by resistance heating. The example considered was the runner of the double spiral fluidity test, of cross-section approximately 4.1 x 3.8 cm., and 19 cm. long. The resistivity of liquid aluminum is approximately 20 micro-ohms.cm at about 1250°F. The specific heat of liquid aluminum is approximately .26 calories per gram degree centigrade, and in order to raise metal in this channel by one degree centigrade per second an intensity of 20,000 amperes would be required. Similar calculations on the effect of induction heat on increasing runner temperature also yielded very low temperature increases, and in several tests conducted passing molten aluminum through induction coils with and without a graphite tube susceptor, no improvement in fluidity was obtained.

E. Conclusions.

1. Fluidity of aluminum - 4.5 per cent copper alloy in plaster molds is approximately 300 per cent greater than that in sand molds, in the range of 1250 - 1350°F. pouring temperatures. This increase is attributed primarily to the low heat diffusivity of plaster.

2. Preheating bentonite-bonded sand molds significantly improves fluidity of aluminum - 4.5 per cent copper alloy. For example, for pouring temperatures in the range of 1250 - 1350°F., increasing the

mold temperature from room temperature to 450°F. improves fluidity by 250 per cent; increasing mold temperature to 610°F. improves fluidity 400 per cent.

3. Calculation and experiment show that temperature losses in runner systems of the types usually employed in aluminum foundries are very small.

4. Maximum heat losses occur at the "leading tip" of metal in a gating system as in a fluidity spiral. However, mixing during the initial flow minimizes the temperature drop in this "leading tip". When mixing during initial flow is a minimum, as in runner choked systems, it is good practice to run the runner past the last ingate to prevent the first cold metal from entering the casting.

5. Methods of instantaneously heating the mold-metal interface during filling of a sand mold were investigated. The purpose of these experiments was to minimize or eliminate heat losses during the filling of a casting cavity, without affecting overall rate of solidification. Experiments were conducted using resistance heating which showed this to be a potentially practical method of improving fluidity.

6. Methods of quickly adding superheat to metal as it passed through a runner system were considered, including (1) resistance heating, (2) induction heating, and (3) induction heating with a graphite susceptor. None of these techniques appeared to be a practical means for increasing fluidity.

V. SUMMARY OF CONCLUSIONS

The following conclusions are derived from work conducted using the vacuum fluidity test apparatus:

1. Vibration (60 cycles per second) applied parallel and perpendicular to direction of flow in the vacuum fluidity test was found to have no effect on fluidity. This was the case even in tubes as small as .07 inches in diameter and at metal heads as low as 3.5 inches.

2. Regardless of melt temperature, a "critical metal head" is necessary to force aluminum into small diameter channels. This critical metal head is that required to overcome surface tension.

3. Calculations based on a series of experiments conducted in normal atmosphere indicated effective surface tension of aluminum - 4.5 per cent copper alloy was 690 dynes/cm. Surface tension in nitrogen atmosphere was calculated to be 590 dynes per centimeter and in oxygen atmosphere to be approximately 920 dynes per centimeter. These values are in general agreement with published data for surface tension of aluminum.

4. Vibration has no effect on the "critical metal head" required to force metal to enter small diameter channels; hence, it apparently has no effect on surface tension.

5. When the metal head in a fluidity test is somewhat greater than the "critical metal head", no significant effect on fluidity is obtained by altering surface effects; e.g., by adding or removing an oxide film.

6. When the metal head in a fluidity test is very low (in the neighborhood of the "critical metal head") surface effects are important in determining fluidity.

The following conclusions are derived from work conducted using sand mold fluidity tests:

7. "Critical metal head" necessary for metal to enter small holes in sand molds was measured and related to surface tension. Data obtained for unvibrated castings indicate the effective surface tension of aluminum - 4.5 per cent copper alloy in sand molds in the order of 800 dynes per centimeter.

8. Beryllium addition has no effect on the ability of aluminum - 4.5 per cent copper alloy to enter small diameter holes.

9. Vibration (60 cycles per second with amplitudes from .001 to .0035 inches) markedly increases the ability of the aluminum alloy to fill small diameter holes. For example, 2 inches below a melt surface the smallest hole metal will enter without vibration is 0.11 inches diameter; with vibration amplitude of .002 inches it can enter a hole .07 inches in diameter and with vibration amplitude of .003 inches it can enter a hole smaller than .02 inches.

10. The effect of vibration in improving the ability of metal to enter small diameter holes is explainable qualitatively and quantitatively on the basis that vibration increases effective metal head.

11. Vibration increases the distance metal runs (fluidity) in small holes in sand molds; this effect is greatest at small metal heads

and is again attributable to increased effective metal head.

12. No increase in fluidity was found from vibration in the case of (a) a standard sand mold fluidity spiral (1/8 inch thick), and (b) a plate-like sand casting (1/8 inch thick).

13. Fluidity of aluminum - 4.5 per cent copper alloy in plaster molds is approximately 300 per cent greater than that in sand molds, in the range of 1250 - 1350°F. pouring temperatures. This increase is attributed primarily to the low heat diffusivity of plaster.

14. Preheating bentonite-bonded sand molds significantly improves fluidity of aluminum - 4.5 per cent copper alloy. For example, for pouring temperatures in the range of 1250 - 1350°F. increasing the mold temperature from room temperature to 450°F. improves fluidity by 250 per cent; increasing mold temperature to 610°F. improves fluidity 400 per cent.

15. Calculation and experiment show that temperature losses in runner systems of the types usually employed in aluminum foundries are very small.

16. Maximum heat losses occur at the "leading tip" of metal in a gating system as in a fluidity spiral. However, mixing during the initial flow minimizes the temperature drop in this "leading tip." When mixing during initial flow is a minimum, as in runner choked systems, it is good practice to run the runner past the last ingate to prevent the first cold metal from entering the casting.

17. Methods of instantaneously heating the mold-metal interface during filling of a sand mold were investigated. The purpose of these experiments was to minimize or eliminate heat losses during the filling of a casting cavity, without affecting overall rate of solidification. Experiments were conducted using resistance heating which showed this to be a potentially practical method of improving fluidity.

18. Methods of quickly adding superheat to metal as it passed through a runner system were considered, including (1) resistance heating, (2) induction heating, and (3) induction heating with a graphite susceptor. None of these techniques appeared to be a practical means for increasing fluidity.

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APPENDIX

Calculation of Temperature Drops in Runner Systems - Comparison with Experiment

Consider molten aluminum flowing horizontally in a long cylindrical runner. Flow rate is constant and no freezing takes place. Heat flow will be considered from a thin wafer element of thickness, dx (Figure 20), as this element moves down the length of the runner. Assuming only radial heat flow, and no temperature gradients within the molten metal in the wafer, the rate of heat flow (per unit length, dx) from metal to mold is*:

$$q_1 = Sh\ (T - T_{SC}) \tag{1}$$

Rate of heat flow in the mold is:

$$q_2 = \frac{Sk'\ (T_{SC} - T_R)}{\sqrt{\pi \alpha}} \quad \frac{1}{\sqrt{\theta}} + \frac{\sqrt{\pi \alpha}}{2R} \tag{2}$$

Since $q_1 = q_2$:

$$q = \frac{Sh\ (T - T_R)}{1 + \dfrac{h\ \sqrt{\pi \alpha}}{k'\ \left(\dfrac{1}{\sqrt{\theta}} + \dfrac{\sqrt{\pi \alpha}}{2R} \right)}} \tag{3}$$

Now, flow rate is such that a time ${}_R$ is required for the element to pass from one end of the runner to the other. Then, the total heat extracted from the time the element enters the runner to the time it leaves is:

* Definition of symbols at end of Appendix.

$$Q = \int_{\theta}^{\theta + \theta_R} q d\theta \qquad (4)$$

and the corresponding temperature drop of the element, ΔT, is

$$\Delta T = \frac{Q}{C \rho A} \qquad (5)$$

Combining (4) and (5)

$$\Delta T = \frac{1}{C \rho A} \int_{\theta}^{\theta + \theta_R} q d\theta \qquad (6)$$

By combining equations (3) and (6) and integrating, temperature drop of metal in a runner system can be calculated as a function of flow rate and time. The computation, however, is laborious and can be simplified when θ_R is small compared to θ (as in most real situations, except in the first second or so of flow).

When θ_R is small compared with θ heat flow may be considered constant between time θ and $\theta + \theta_R$. Then, rate of heat transfer per unit length is as given by equation (3) at any time θ . For an element of metal of length dx, the heat loss during θ_R is (per unit length):

$$Q = q \theta_R \qquad (7)$$

and temperature drop is:

$$\Delta T = \frac{Q}{C \rho A \Delta T} \tag{8}$$

combining (3), (7), and (8):

$$\Delta T = \frac{Sh\ (T-T_R)}{C\ \rho\ A} \times \frac{\theta\ R}{1 + \dfrac{h\ \sqrt{\pi\alpha}}{k'\ \left(\dfrac{1}{\sqrt{\theta}} + \dfrac{\sqrt{\pi\alpha}}{2R}\right)}} \tag{9}$$

Comparison with Experiment

In tests at M.I.T. in the course of this research temperature drops were measured in a runner system designed to simulate types of runners in general to practical use. The runner was 1 inch in diameter, 16 inches long. Metal head was 7 inches. Thermocouples were placed at the entrance and exit points of the channel and preheated electrically to minimize response time.

Numerical values of experimental variables were:

S	=	8 cm.		ρ	=	2.6 gm/cm^3 (pure Al)
h	=	0.07 $^{cal}/cm^2.sec.{}^oC$		C	=	.26 cal/gm (pure Al)
T-Tr	=	730°C.		k'	=	10^{-3} cal/sec.cm.°C
R	=	1.27 cm.		α	=	2.5 . 10^{-3} $cm^2/sec.$
A	=	5.1 cm^2		θ_R	=	.2 sec.

Maximum temperature drop measured was approximately 5°F. This maximum drop measured occurred a second or two after start of pour and compares favorably with temperature drops calculated from equation (9), i.e.:

Calculated Temperature Drop

θ (sec)	ΔT (°F.)
1	6.3
4	3.6
25	1.6
100	0.9

As further comparison of experiment with theory, data obtained at Alcoa Research Laboratories was analyzed using the same mathematical approach.[16] The Alcoa work was performed with 356 alloy in sodium silicate bonded molds, but mold and metal properties were assumed similar to that of work at M.I.T.

Numerical values of experimental variables, used for calculation were:

$S = 6$ cm.
$h = 0.07$ cal/cm²·sec·°C
$T - T_R = 680$°C.
$R = .85$ cm.
$A = 2.85$ cm^2
$\rho = 2.4$ gm/cm^3
$C = 0.23$ cal/gm
$k' = 10^{-3}$ cal/sec·cm·°C
$\alpha = 2.5 \cdot 10^{-3}$ cm^2/sec.
$\theta_R = 2.25$ sec.

Results show very close agreement with calculations, Figure 21; calculated temperature drops were:

Calculated Temperature Drop

θ (sec)	ΔT (°F.)
1	58
4	32.5
25	15.5
100	9.5

It should be noted that while quite large temperature drops are calculated even after 1 second of flow (and obtained experimentally), this is because of the very low flow rates (long θ_R) used.

In general summary:

1. A simplified analysis developed in this work permits precise calculation of temperature drops in runners; results obtained agree with experiment.

2. The analysis employed assumes a coefficient of heat transfer, h, (between mold and metal) of 0.07 $^{cal}/cm^2.sec.°C$ as determined from earlier work at M.I.T. on fluidity. However, for times over several seconds, variations of h from less than 0.07 to infinity do not appreciably affect total temperature drop.

3. The analysis developed does not apply for approximately the first second, or fraction thereof of pouring time, because of simplifying assumptions employed. However, more involved mathematics would probably not be of use during this first second (unless the model of flow were substantially modified) because of turbulent mixing during filling of the runner system.

4. Calculation and experiment indicate that temperature losses in runners used commercially are generally quite small, almost always less than 10°F. in the case of aluminum alloys. Additional losses occur in sprues and gates but a preliminary conclusion can be reached that fluidity in sand castings is ordinarily not greatly reduced by heat losses in the runner system.

5. Maximum heat losses occur at the "leading tip" of metal in a gating system as in a fluidity spiral. However, mixing during the initial flow minimizes the temperature drop in this "leading tip". When mixing during initial flow is a minimum, as in runner choked systems, it is good practice to run the runner past the last ingate to prevent the first cold metal from entering the casting.

List of Symbols

A:	mold surface area, cm^2
C:	specific heat of metal, $^{cal}/gm.\ ^{\circ}C.$
C_p:	specific heat of mold, $^{cal}/gm.\ ^{\circ}C.$
h:	heat transfer coefficient at mold-metal interface, $^{cal}/cm^2 sec.^{\circ}C.$
k':	thermal conductivity of mold, $^{cal}/sec.cm.^{\circ}C.$
Q:	total heat entering mold, $^{cal}/cm.$
q:	heat flow rate from metal to mold, per unit length $^{cal}/cm.sec.$
R:	radius of mold channel, cm.
S:	circumference of mold channel, cm.
T:	temperature of liquid metal, °C.
T_R:	room temperature, °C.
T_{SC}:	mold temperature at interface, °C.
ΔT:	temperature drop, °C.
α :	thermal diffusivity of mold = $\dfrac{k'}{\rho_m \times C_p}$, $cm^2/sec.$
ρ :	metal density, gm/cm^3
ρ_m :	mold density, gm/cm^3
θ :	time, sec.
θ_R:	residing time of metal in runner, sec.

TABLE I

Fluidity of aluminum -4.5 per cent copper alloy in vibrated test tubes

Vibration and tube diameter	Metal Head (inches)	Melt Temperature (°F)	Fluidity (cm)	
			Vibrated	Control
Lateral vibration, tube diameter 5 mm	2	1364	16.5	15.5
	12	1288	22	21.5
Lateral vibration, tube diameter 4 mm	2	1288	14.5	14.5
	23.5	1288	17.5	17.0
Longitudinal vibration, tube diameter 3 mm	5	1288	9.9	9.8
	30	1288	18.8	18.5

Note: Data are averages of two or more individual tests.

TABLE II

Effect of atmosphere on surface tension in vacuum fluidity test.

Tube diameter (inches)	Atmosphere	Metal head necessary to bring level of aluminum in tube equal to that in bath (inches)	Calculated surface tension (dynes/cm)
.20	Nitrogen	.73	550
.07	Nitrogen	2.35	625
0.20	Oxygen	1.22	920

TABLE III

Sand castings poured to determine effect of vibration on fluidity.

Casting No.	Treatment	Vibration amplitude (inches)	Pouring temperature (°F)
1	No vibration	-	1470
2	No vibration	-	1420
3	No vibration	-	1370
4	No vibration	-	1370
5	No vibration (0.5% be added)	-	1370
6	Vibration	.003	1470
7	Vibration	.001	1370
8	Vibration	.002	1370
9	Vibration	.0025	1370
10	Vibration	.0035	1370
11	Vibration (after pour)	.0035	1370
12	Vibration (after pour)	.003	1370

TABLE IV

Effect of vibration amplitude on minimum size hole molten aluminum - 4.5%copper alloy will enter. Comparison of calculation with experiment.

Vibration amplitude (inches)	Minimum diameter hole aluminum - 4.5% copper alloy will enter					
	Metal height = 3 cm (1.18 inches)		Metal height = 5 cm (1.97 inches)		Metal height = 8 cm (3.16 inches)	
	Calculated min. diam. (inches)	Observed min. diam. (inches)	Calculated min. diam. (inches)	Observed min. diam. (inches)	Calculated min. diam. (inches)	Observed min. diam. (inches)
0	.18	.18	.11	.11	.07	.07
.001	.13	.11	.08	.09	.05	.055
.002	.10	.10	.06	.07	.04	.05
.0025	.095	.07	.055	.05	.035	.04
.0030	.085	.02	.050	.02	.032	.02
.0035	.078	.02	.046	.02	.029	.02

Note: "Calculated" minimum diameters are from equation (7): data for "observed" minimum diameters are from Figure 13.

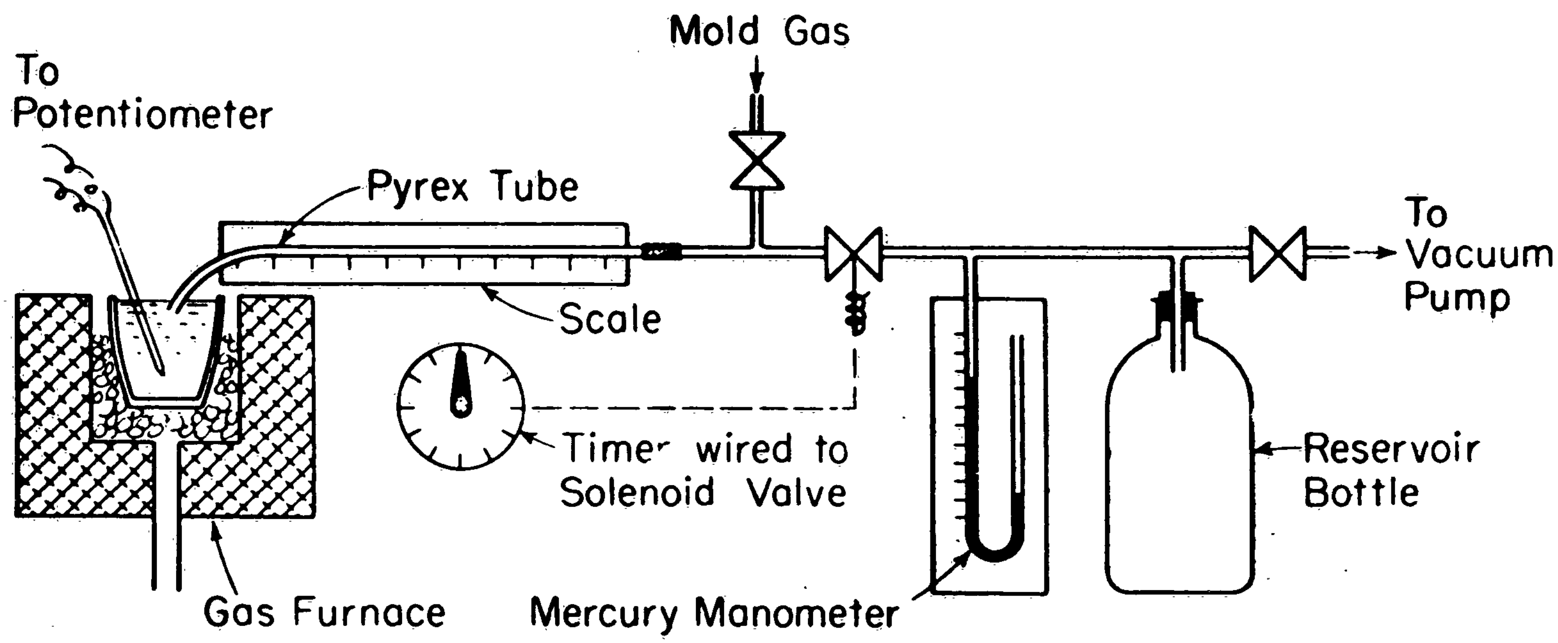


Figure 1. Sketch of vacuum fluidity test apparatus.

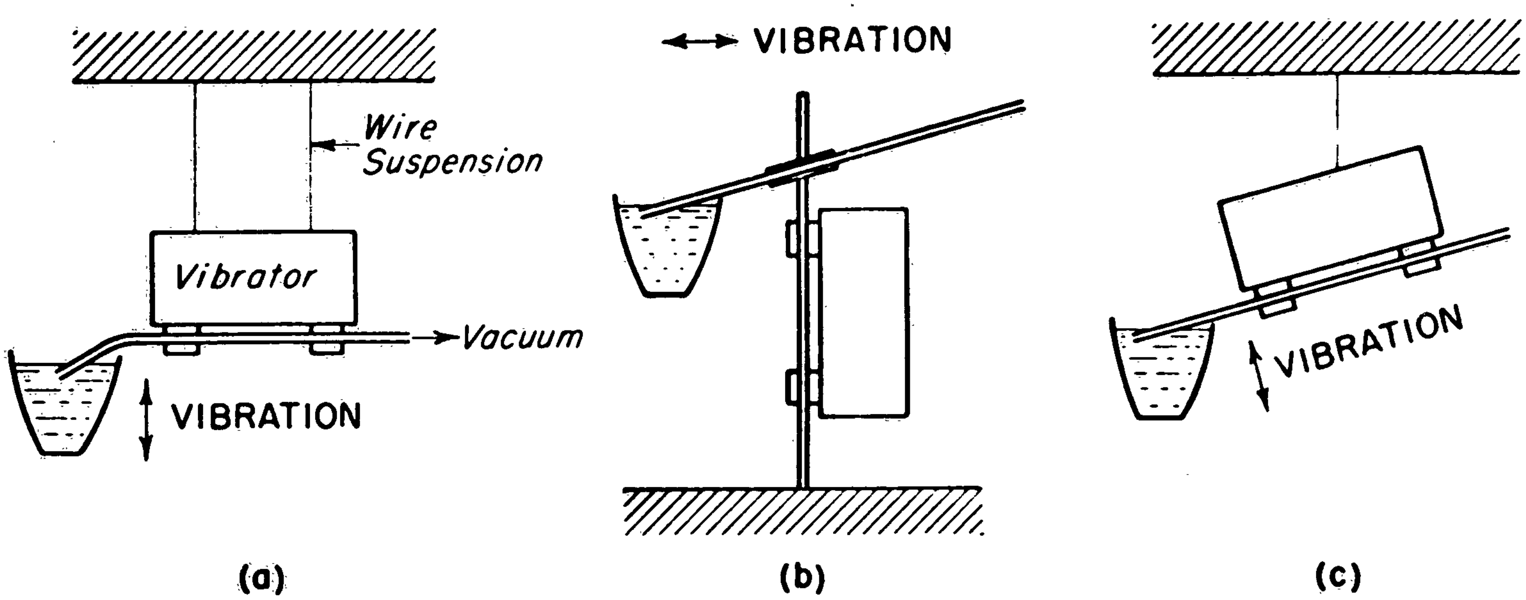


Figure 2. Sketch of apparatus for application of vibration in vacuum fluidity test.

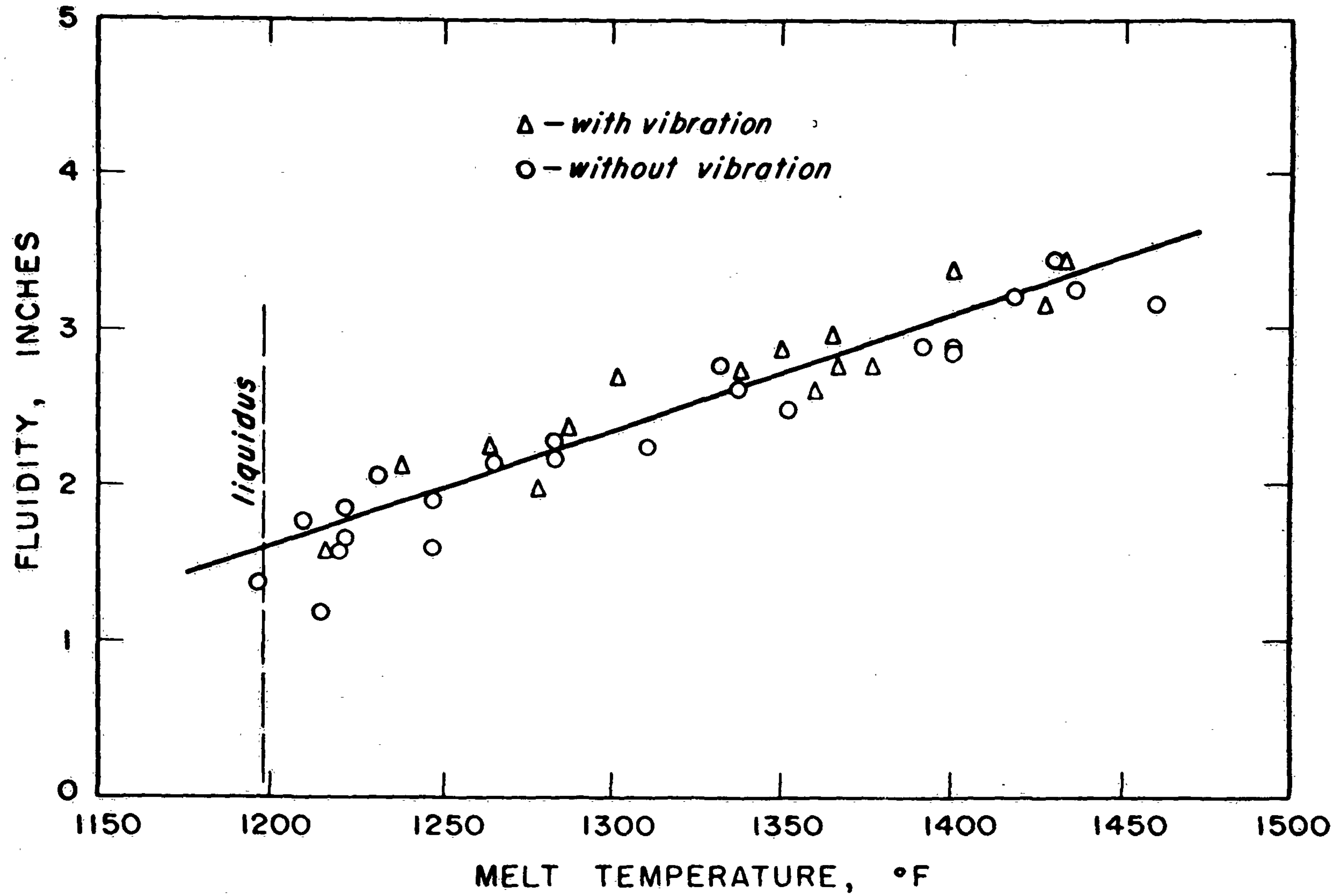


Figure 3. Results of initial tests conducted to determine effect of vibration on fluidity in small diameter tubes. Tubes employed were .06 inches (1.5 mm diameter); pressure head was 30 inches. Vibration had no effect on fluidity.

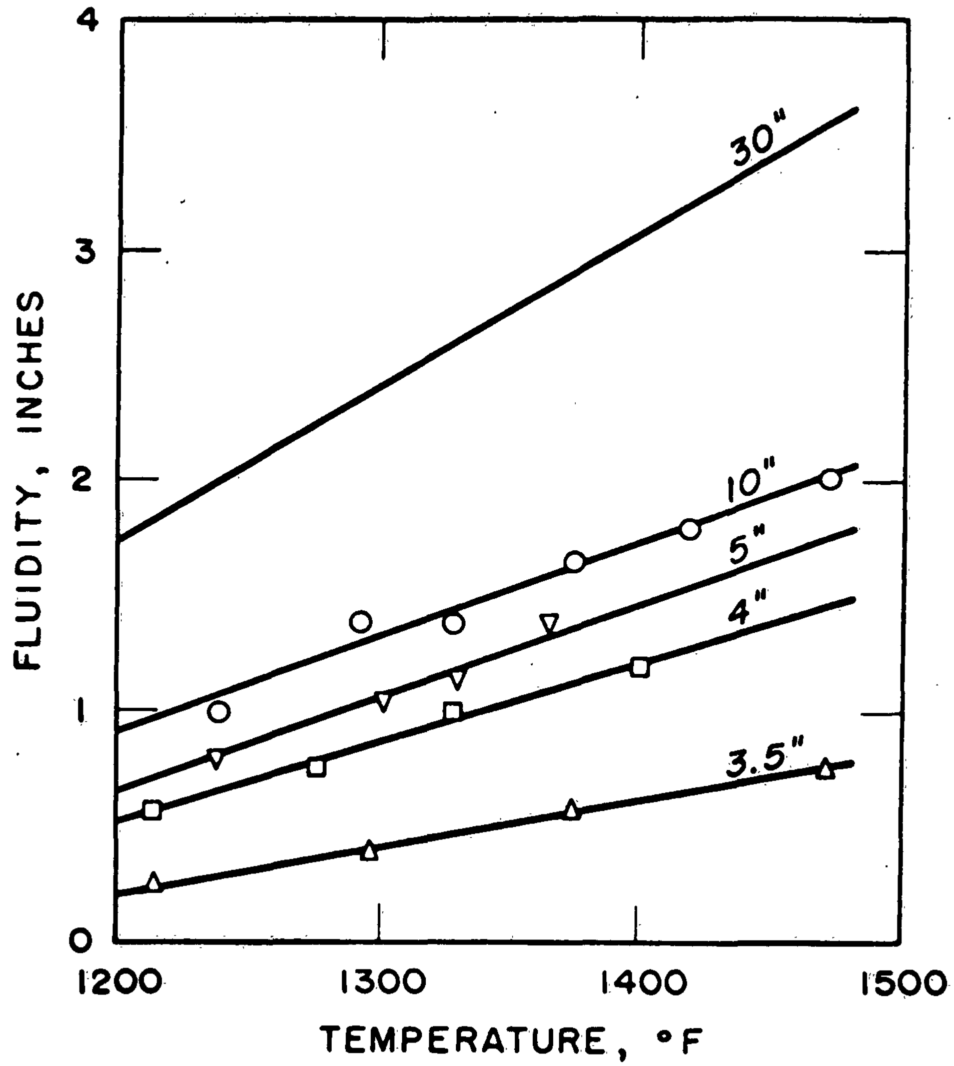


Figure 4. Results of studies to determine effect of vibration on fluidity in small diameter tubes.

Data shown are for tubes .07 inches diameter, metal heads 3.5 to 30 inches, and no vibration. Vibration had no effect on fluidity at any metal head.

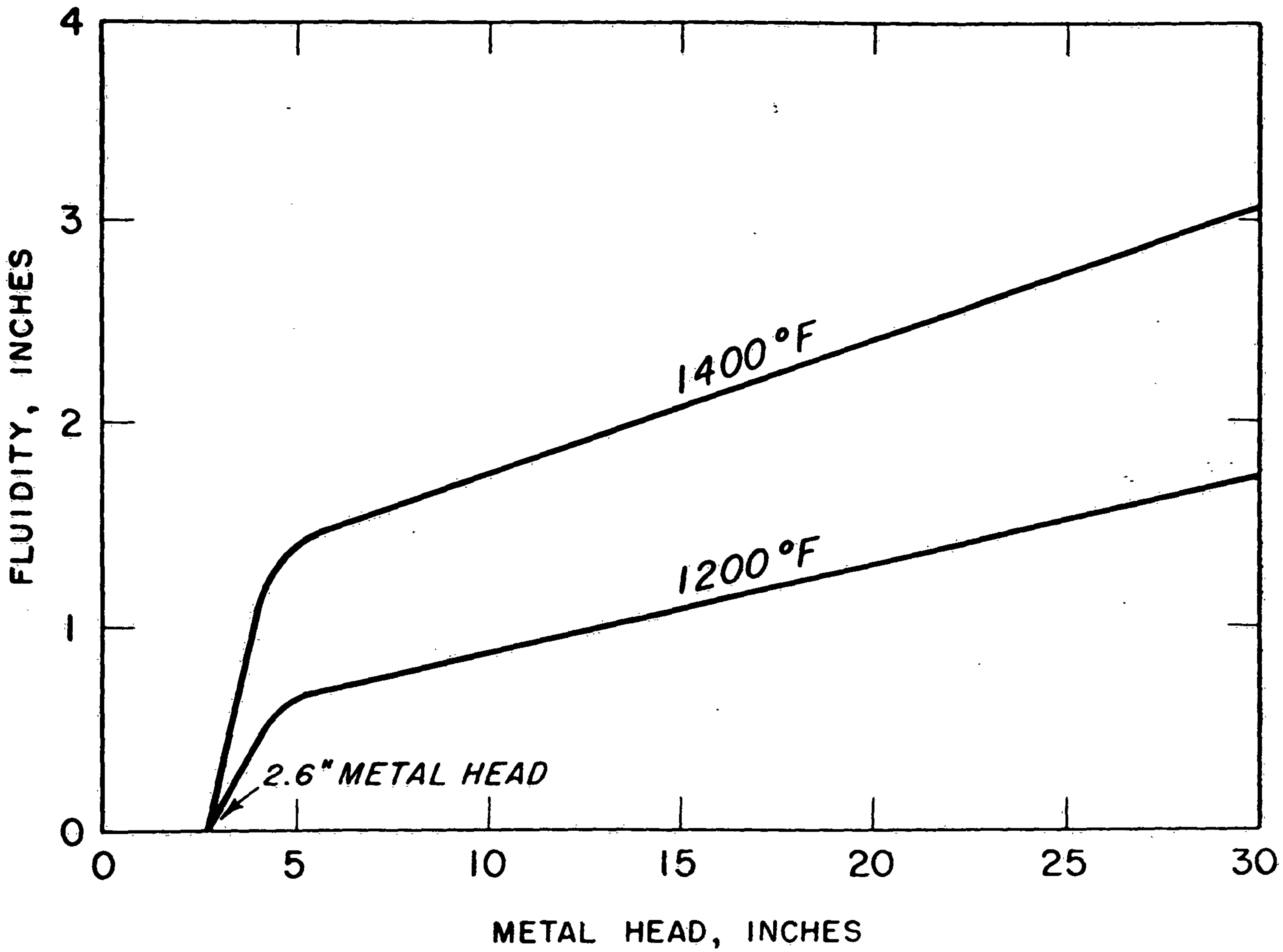


Figure 5. Fluidity versus metal head for tubes .07 inches diameter; two different melt temperature (data replotted from Figure 4).

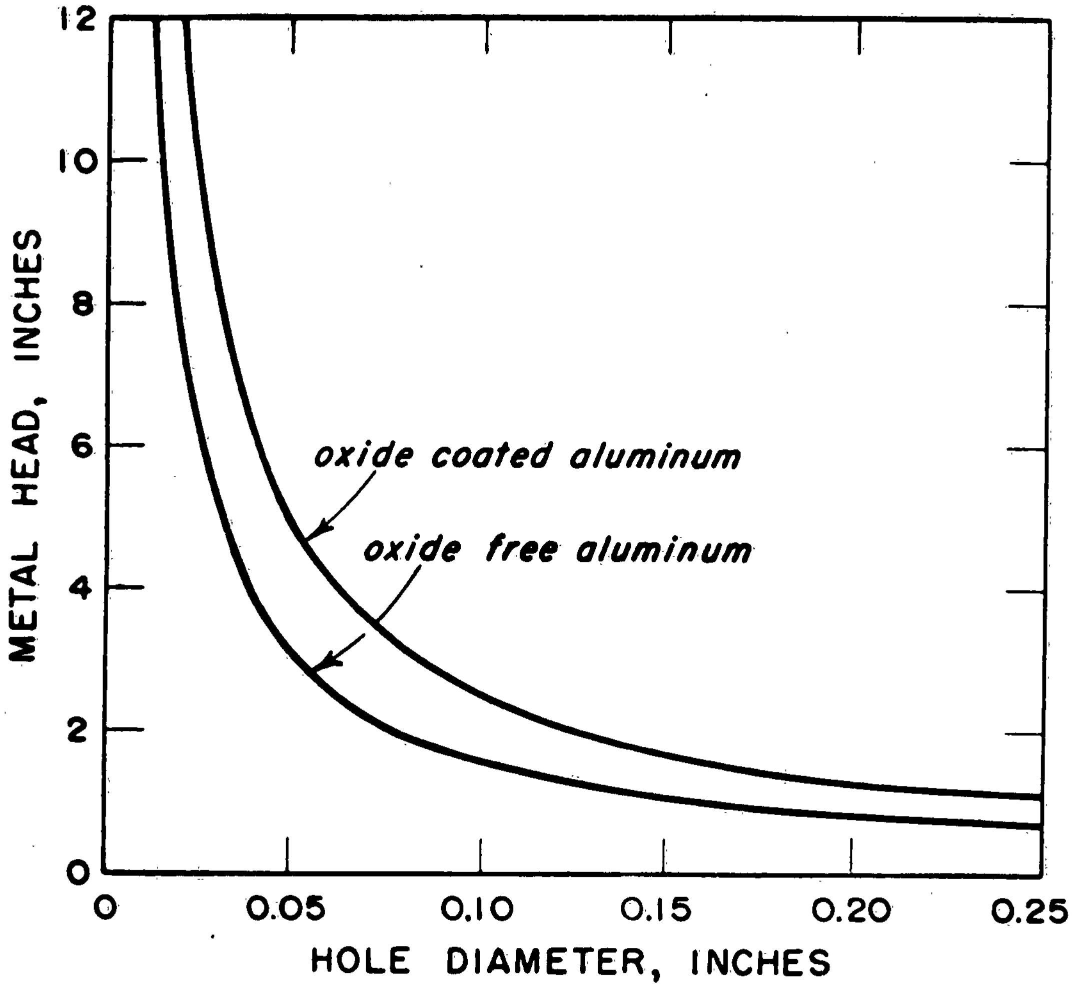


Figure 6. Metal head required to overcome sur e tension of aluminum.

Curves calculated, assuming surface tension of oxide-coated aluminum to be 920 dynes/cm., and surface tension of oxide-free aluminum to be 590 dynes/cm.

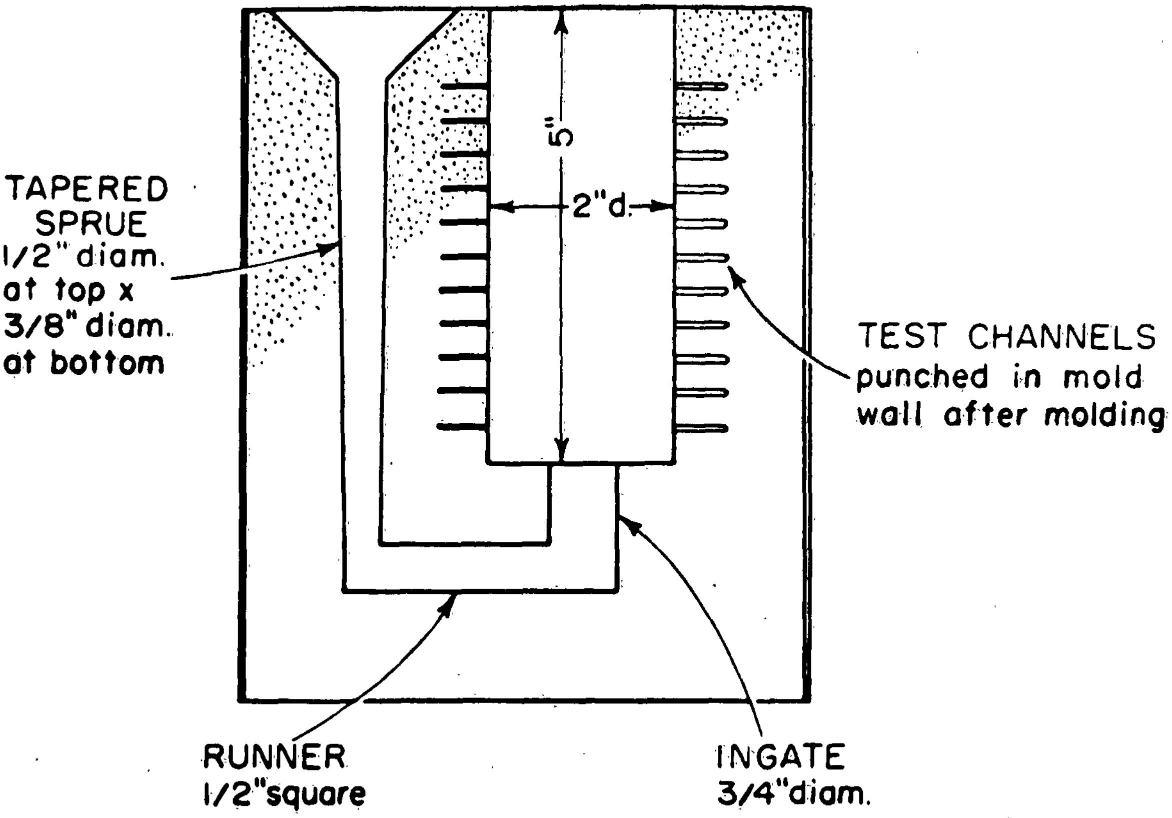


Figure 7: Sketch of mold for cylinder test casting. Diameter of test channels was .020" to .200".

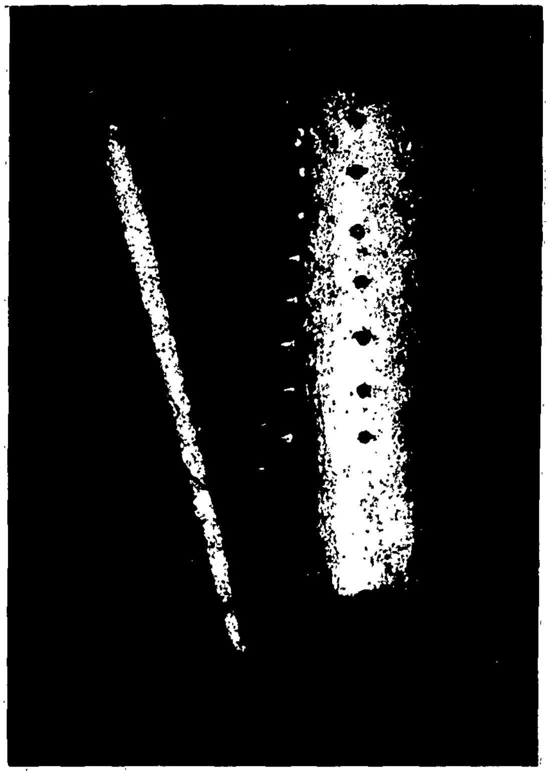


Figure 8. Photograph of typical test casting

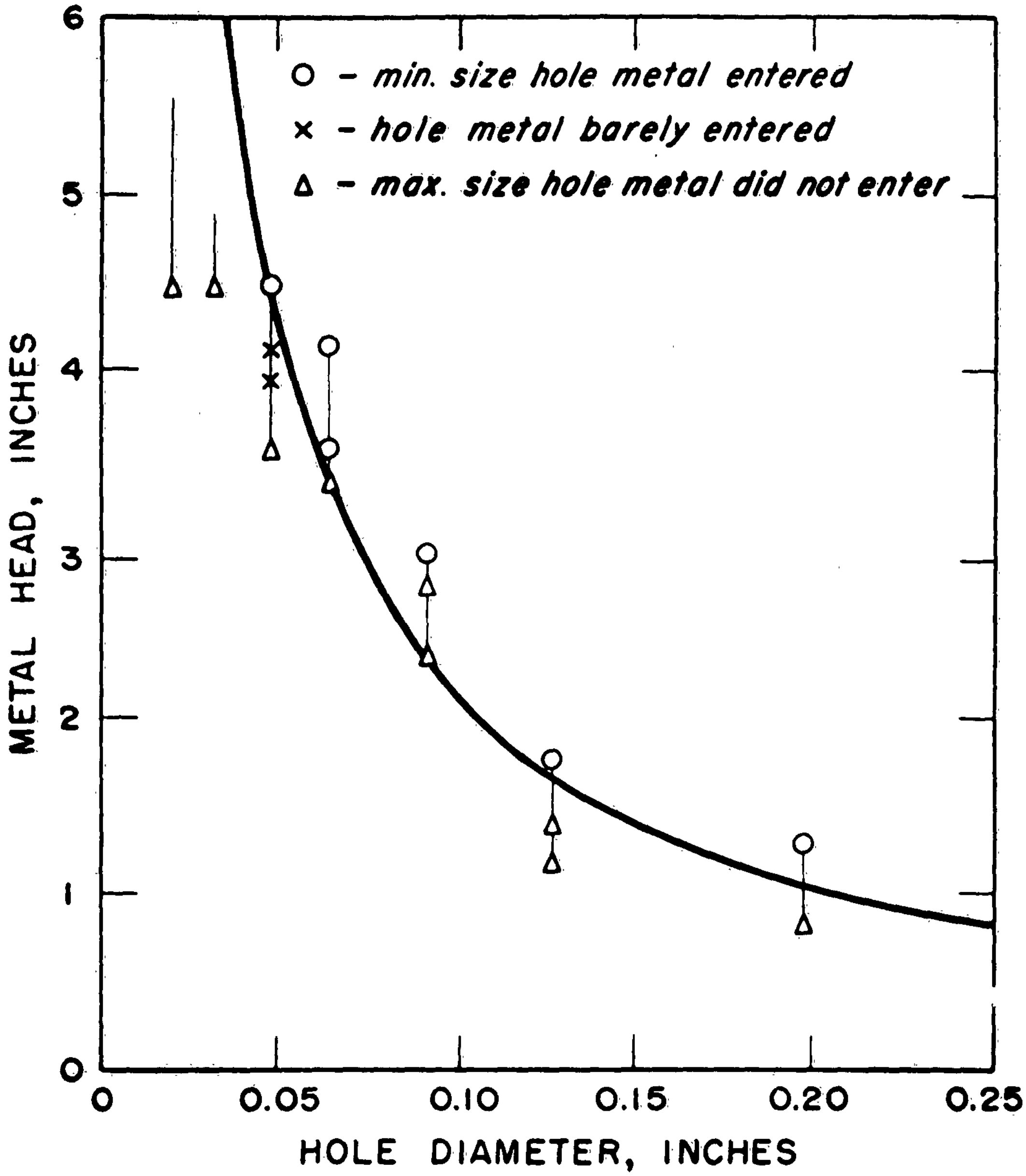


Figure 9. Minimum metal head necessary to force metal into small diameter holes. Curve corresponds to surface tension (γ) equal to 800 dynes/cm.

Typical example, unvibrated casting (casting #1).

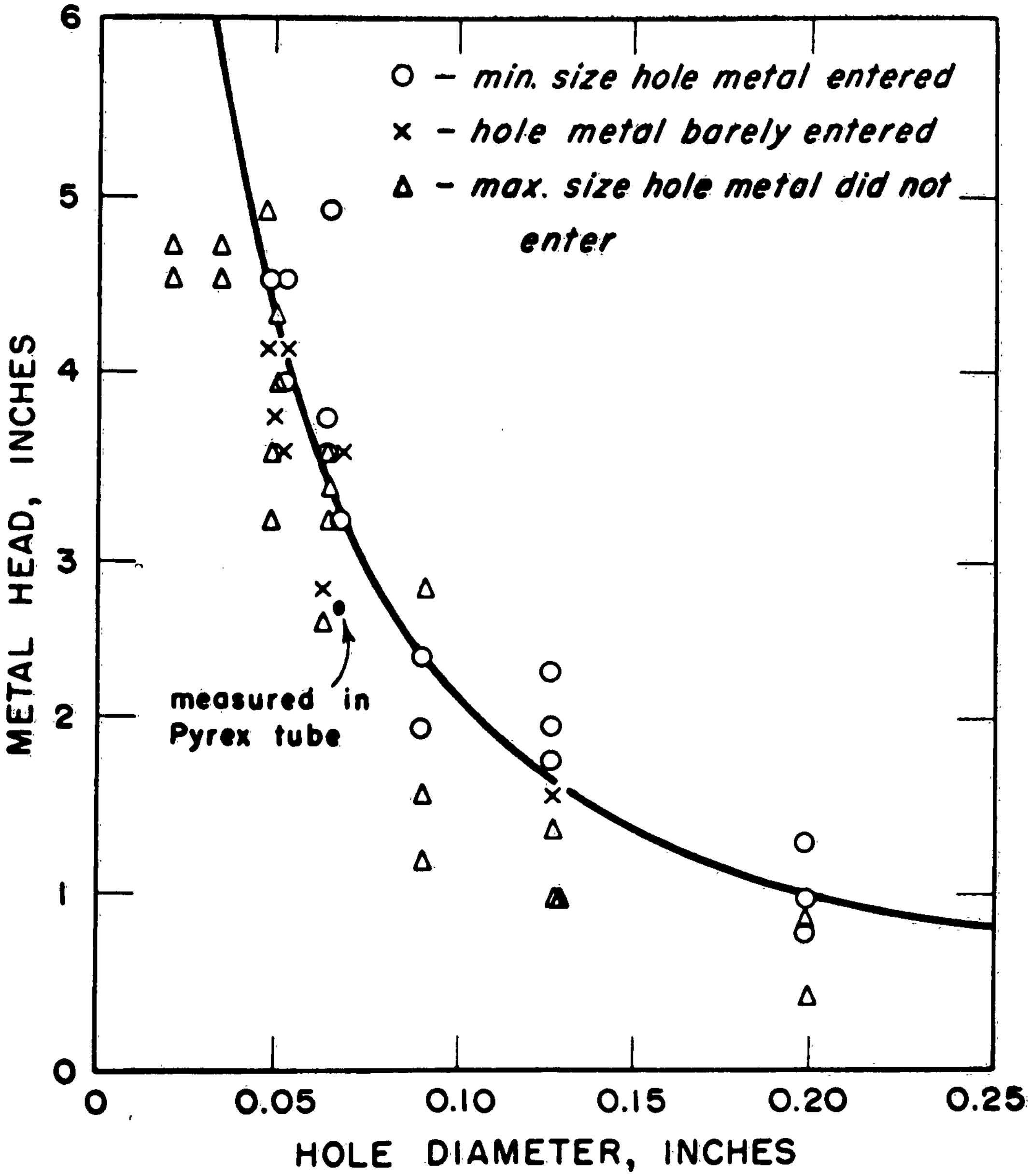


Figure 10. Minimum metal head necessary to force metal into small diameter holes. Curve corresponds to surface tension (γ) equal to 800 dynes/cm.

Data from four unvibrated castings (casting No.'s 1, 2, 11, and 12).

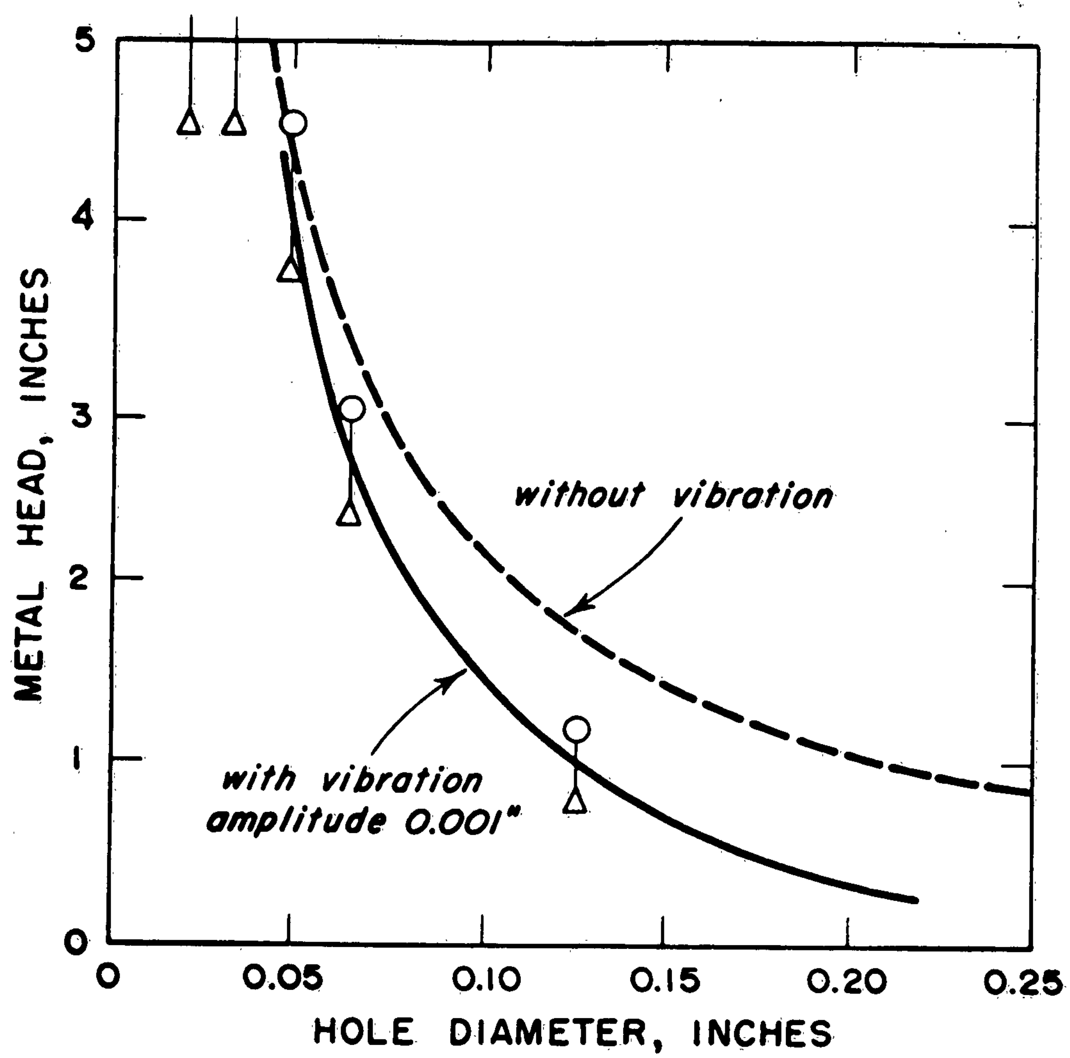
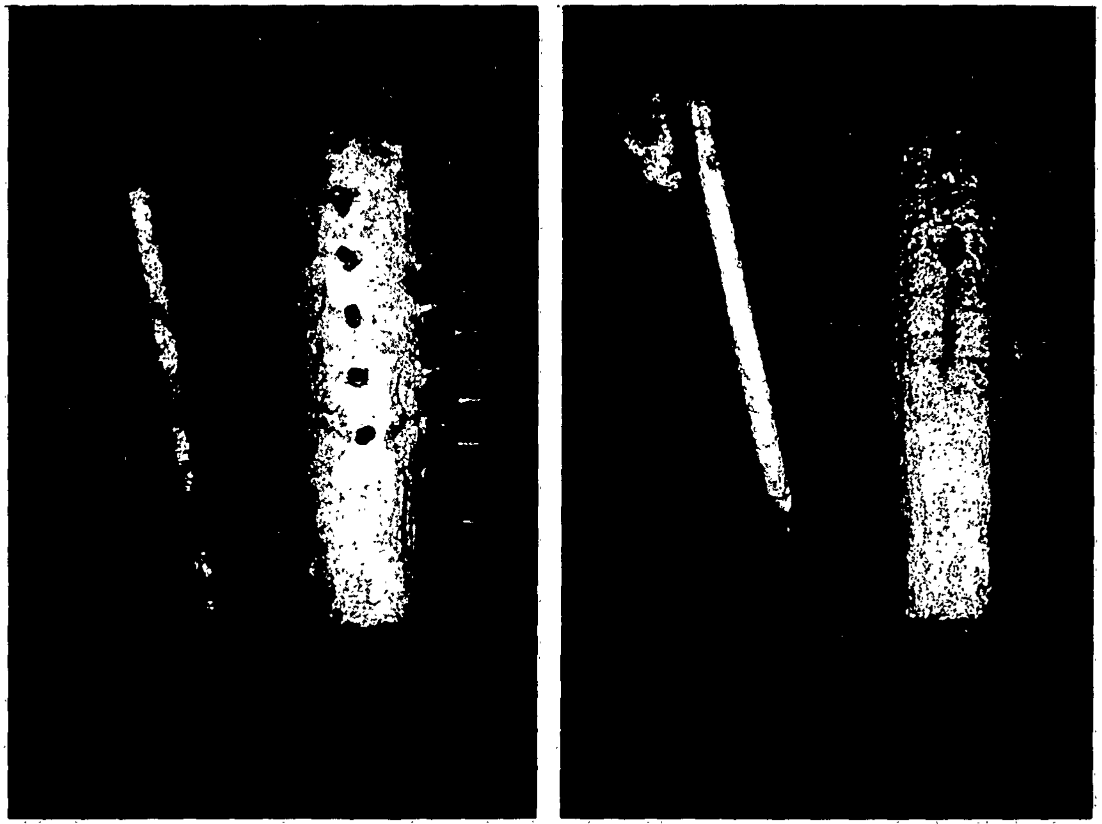


Figure 11. Effect of vibration on minimum metal head necessary to force metal into small diameter holes. Typical example (casting No. 5).

Dashed curve corresponds to γ = 800 dynes/cm.



(a) (b)

Figure 12. Comparison of vibrated and unvibrated test castings.
(a) Vibrated vertically, amplitude = 0.006".
(b) Unvibrated.

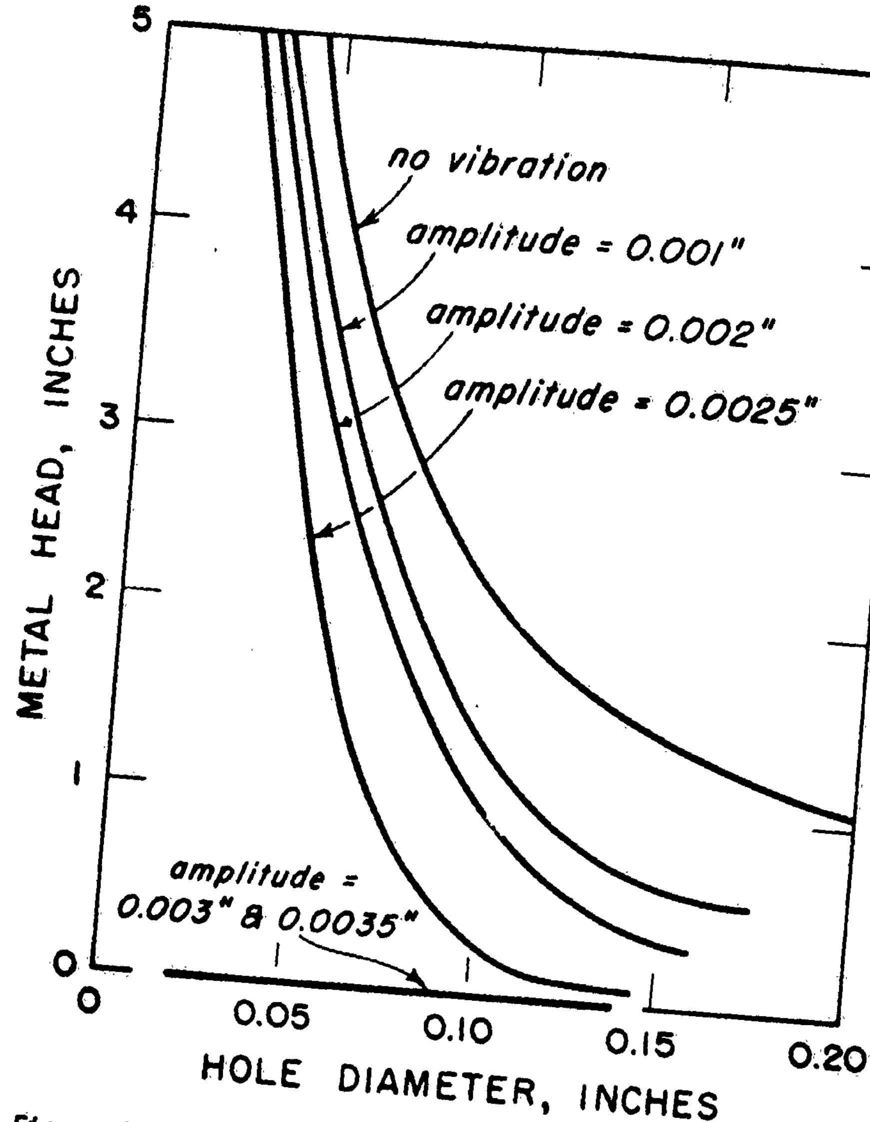


Figure 13. Effect of amplitude of vibration on minimum metal head necessary to force metal into small diameter holes.

Data from castings 1 - 3, 5 - 8, 11 - 12.

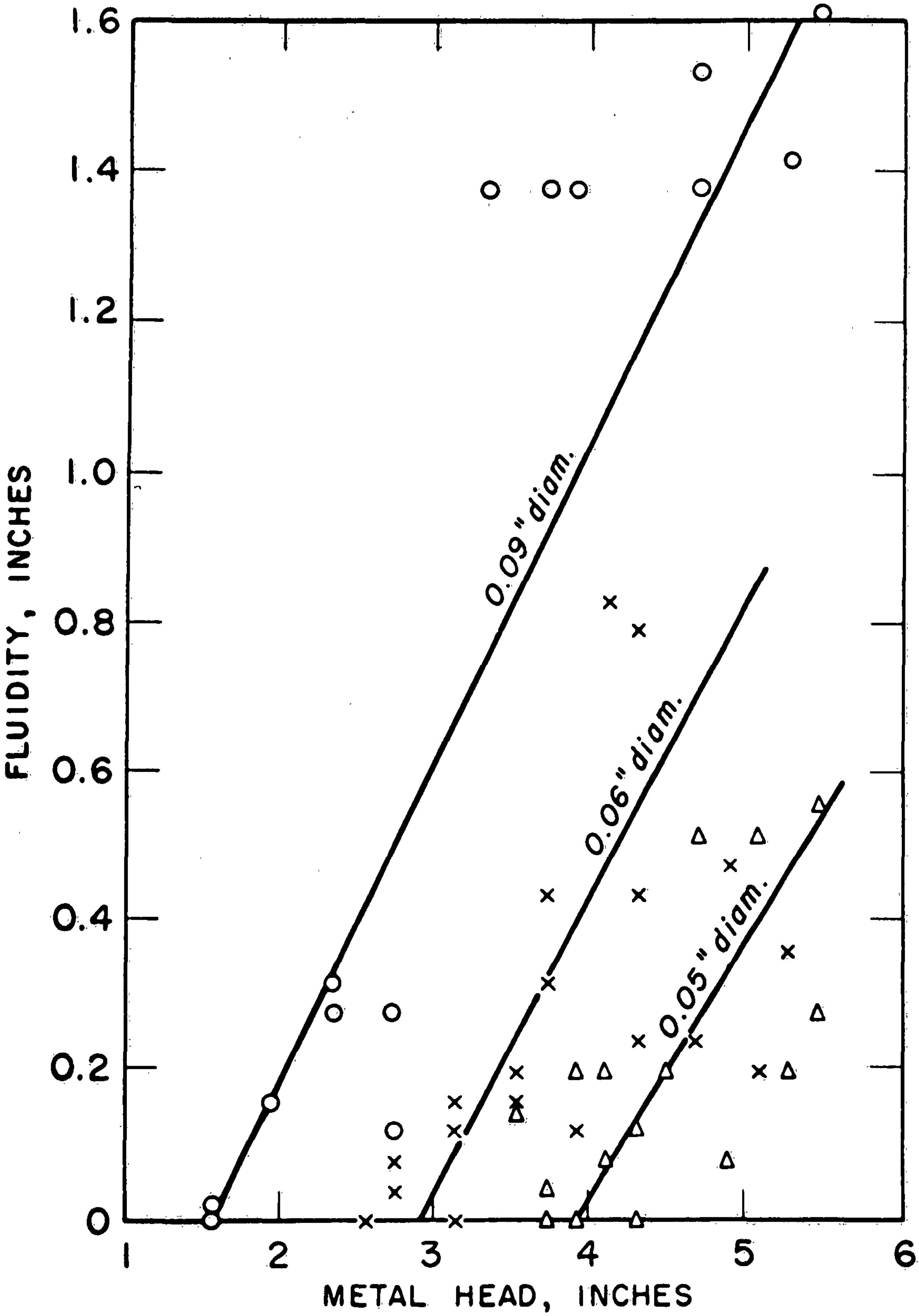


Figure 14. Fluidity versus metal head for three different size holes. No vibration. Castings 3 and 4.

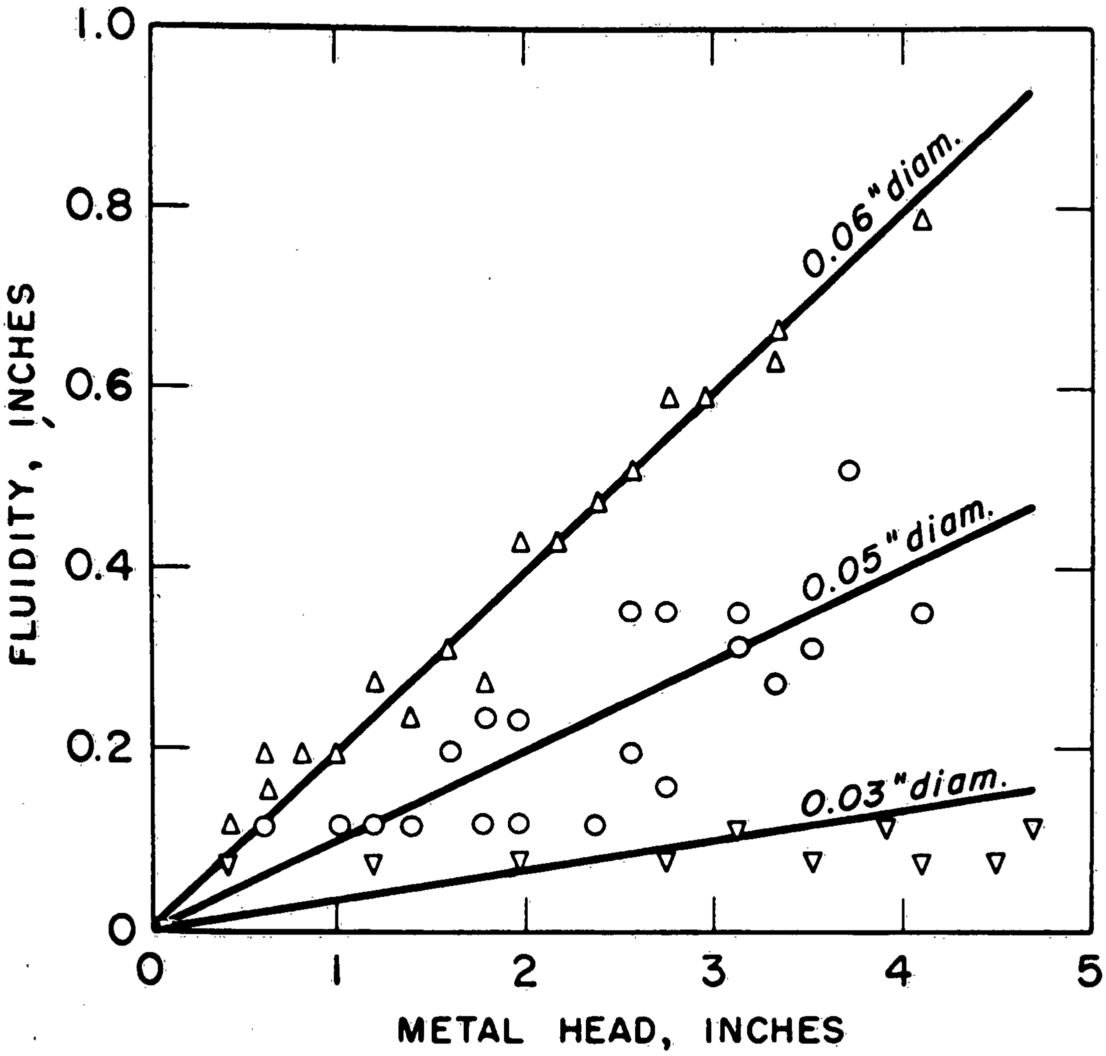


Figure 15. Fluidity versus metal head for three different size holes. With vibration amplitude, 0.0035 inch (Casting No. 10).

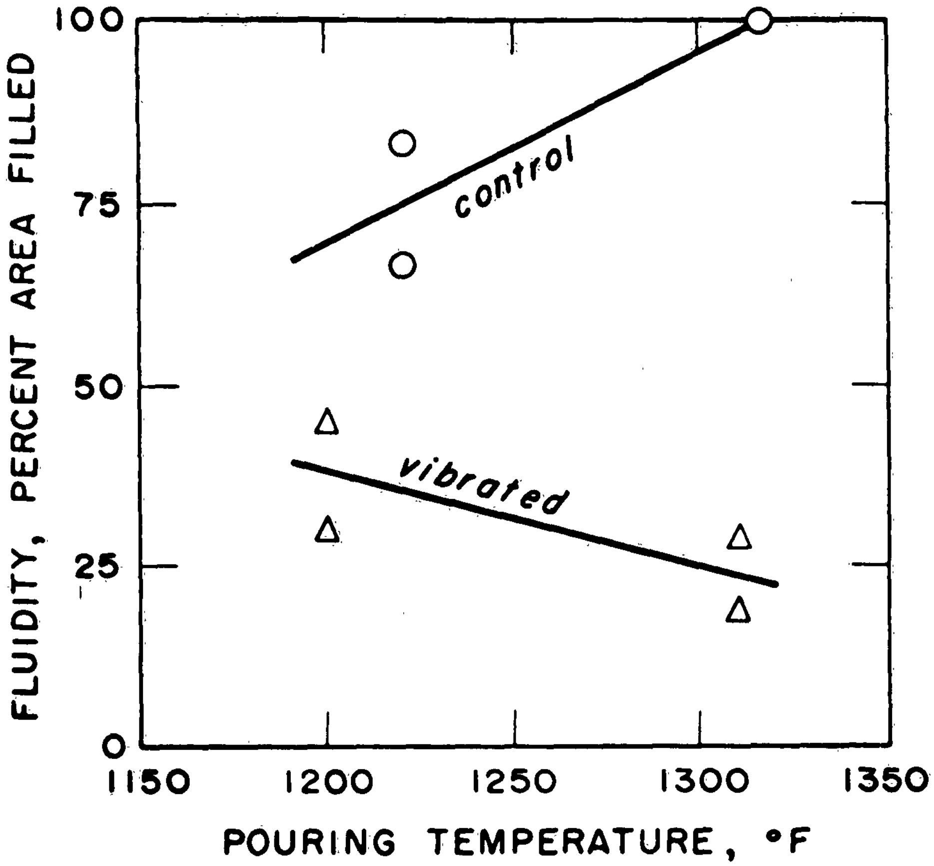


Figure 16. Effect of vibration on fluidity in the flat plate test pattern (5" x 5" x 1/8" thick).

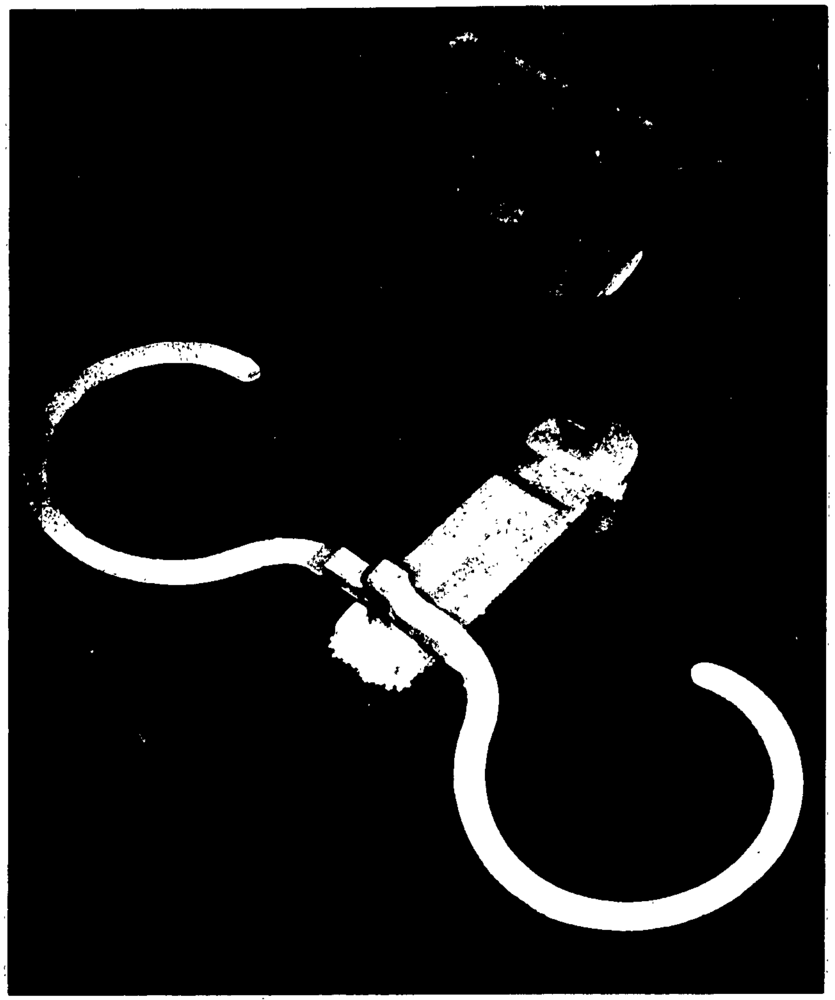


Figure 17. Sand mold fluidity test casting with gating system.

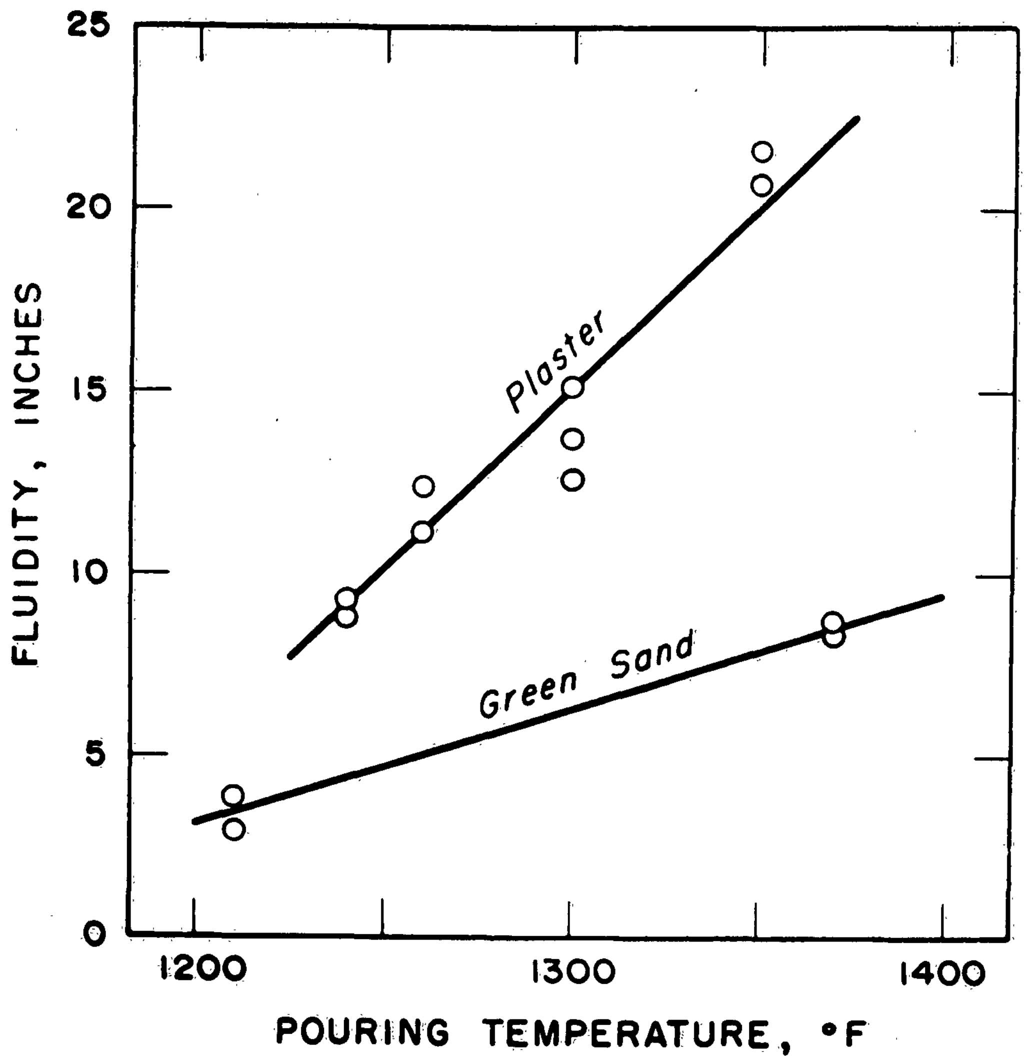


Figure 18. Fluidity of aluminum - 4.5 per cent copper alloy in silica sand and plaster. Sand was bentonite bonded, baked, and of 110 A.F.S. fineness number.

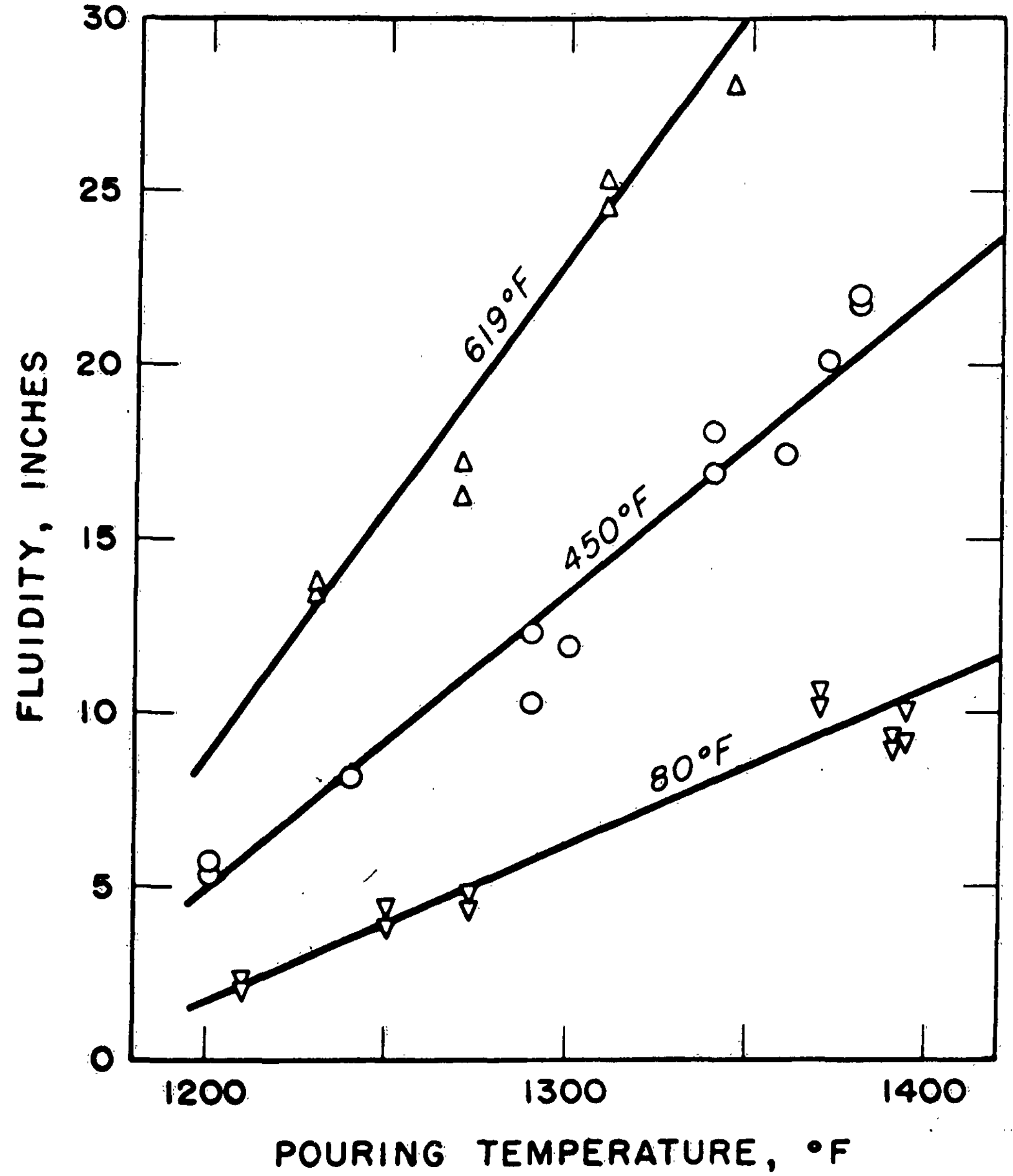


Figure 19. Fluidity of aluminum - 4.5 per cent copper alloy in heated silica sand molds.

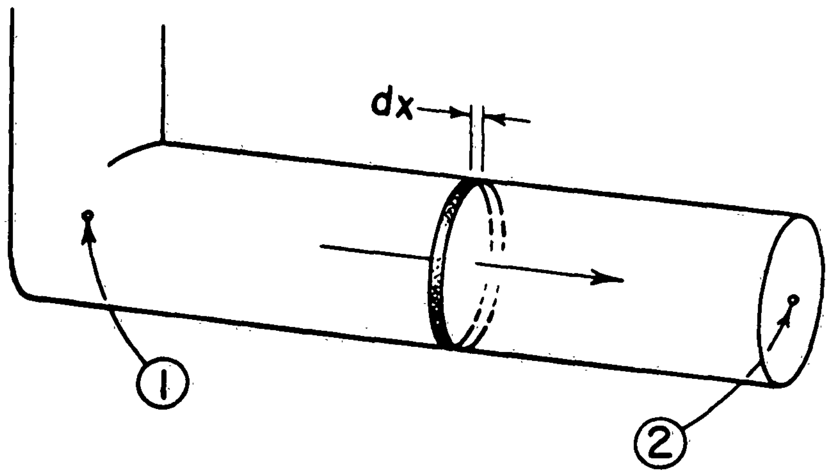


Figure 20. Model for studying heat losses in runners experimentally and analytically.

Temperature was measured at points (1) and (2) (runner entrance and exit, respectively). Heat losses were calculated by assuming radial heat flow from an element dx (shown) moving from point (1) to point (2).

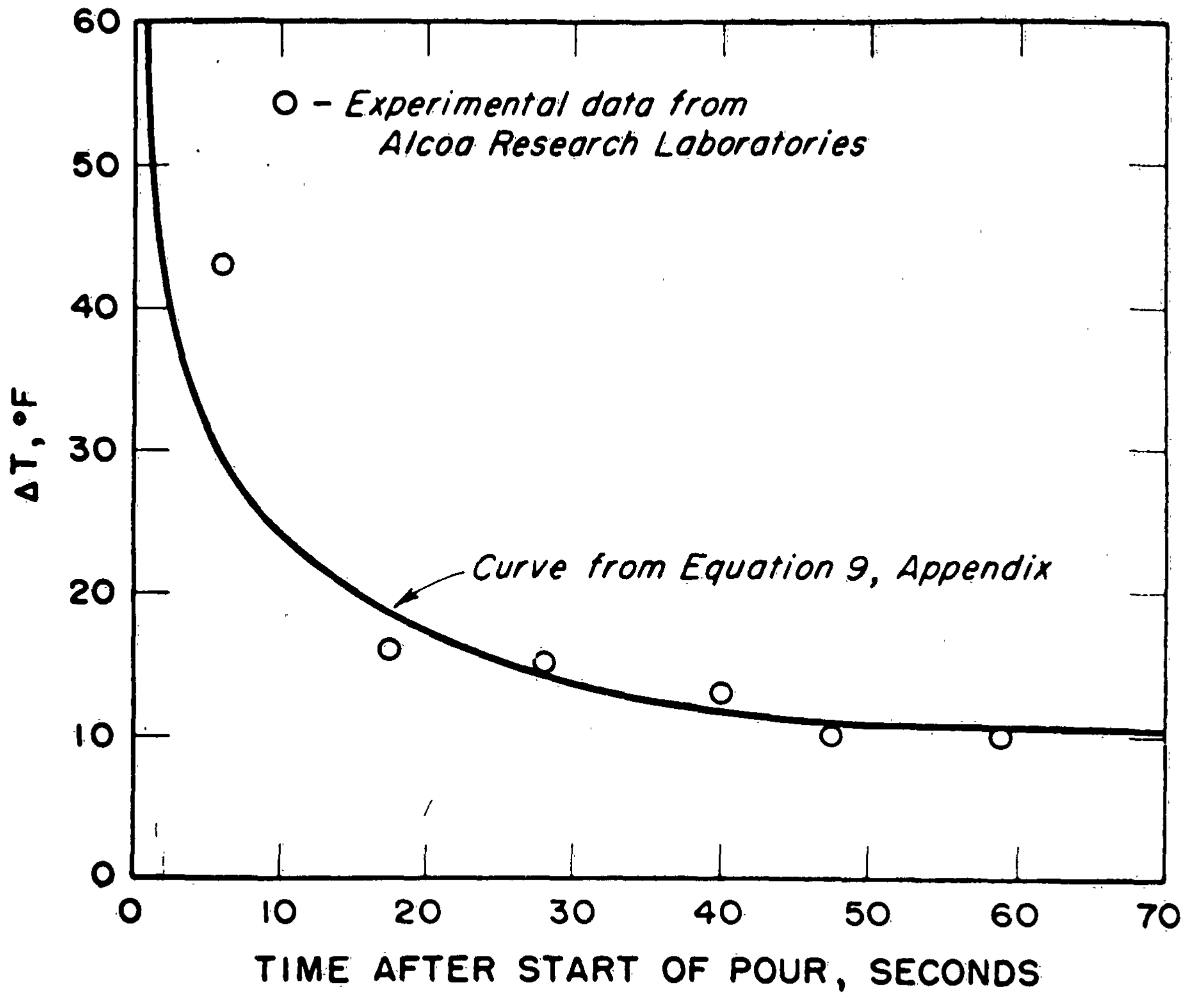


Figure 21. Heat loss in a long cylindrical runner versus time (aluminum alloy 356). Experimental data from work at Alcoa Research Laboratories[16].